Saimaa University of Applied Sciences
Technology, Lappeenranta
Degree Programme in Civil and Construction Engineering

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MOISTURE CALCULATION ANALYSIS AND INJECTION METHODS IN BRICK MASONRY WALLS

Bachelor's Thesis 2010

ABSTRACT
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Moisture Calculation analysis and injection methods in brick masonry walls,
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Saimaa University of Applied Sciences, Lappeenranta
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Bachelor´s Thesis 2010
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Supervisor: Mr Jukka Huttunen, Vahanen group

The main aim of the thesis was to study solid brick masonry cellar walls with high water content and determine possible ways to reduce water content. Evaluation was done via the WUFI 2D 3.3. In addition, my task was to investigate most common repairing methods respective of moisture problematic in brick structures. The thesis was made at Vahanen group in Helsinki, Finland. My main supervisor in Vahanen was Mr Jukka Huttunen. Mr Timo Lehtoviita and Mr Tero Liutu were responsible for the supervison of the work in SUAS,Lappeenranta. I would like to say a few words of gratitude to the above mentioned persons for the opportunity to make this work.

In the thesis solid brick masonry wall with normal lime cement plaster on both interior surfaces in the cellar have been considered. Then was determined the time from which structure absorb maximum amount of water and became in the equilibrium conditions. After that we used rehabilitation technologies to reduce already known total amount of water, such as plasters with high porosity and water proofing injections. The main problem was necessity to create climate file respective water level conditions. In my work injection technologies respective of moisture in cellar walls have also been considered.

The results of the study show that the best method for repair cellar walls with high dampness, caused by rising capillary water, is using high porosity plasters with horizontal damp proofing (injection). Results which we get show that WUFI 2D can be used for modelling rising water in the cellar walls with satisfactory accuracy. Also very interesting dependence between temperature and relative humidity on the different sides of the structure was observed. The presence of different temperatures on the surfaces sufficiently increase total amount of water in the structure.

Different types of injection technologies were considered: pressure injection, unpressurised injection and impulse injection. All considered technologies have got limits of applicability and their own advantages and disadvantages. But can be distinguished impulse injection technology, which has got a lot of advantages, for instance: preparation of the masonry, such as the filling of cavities, is not necessary; the injection process is controlled electronically and the method runs autonomously.

Keywords: WUFI 2D, Brick masonry wall, Water Content, Relative Humidity

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1. INTRODUCTION

In this bachelor thesis the influence of moisture on the cellar wall and possible ways for it is reconstruction was considered. It is very important to understand which harmful factors influence on the structure, because wrong reconstructions and unsuitable products can cause more damage than help to solve the problems. Often compromises have to be made when searching for a complete and long lasting solution and one that is affordable for the owners. The intrinsic value of the building must be considered, and the technical and functional requirements of today’s living have to be in accord with those of preservation.

So one of the greatest challenges is to eliminate the causes of the damages and not only conceal the symptoms and at the same time keep the budget within reasonable bounds. The cause of moisture penetration in most cases can be found in the construction components that are in contact with the ground, where moisture is absorbed and distributed over the entire masonry by capillarity. Here the moisture is the catalyst for most building damages- whether biological, chemical or physical damage processes. (Frossel, 2006)

Injections are the most commonly used method for, or rather, against rising damp. Injection techniques (chemical methods) have become established across the market over the last few decades. They currently take up a market share of about 70 %, with a tendency to increase. (Frossel, 2006)

2. PURE EXPLANATION OF MOISTURE IN MASONRY WALLS

In this part have given pure explanation of process occurred in the materials contacting with liquid. Moisture transport processes in masonry wall have considered. Also at this part have spoken about materials properties used in investigation.

2.1. Porosity of materials

Porous materials because of their generally good heat-insulating properties, have been (and are) used almost exclusively. Mineral materials are composed of binders, additives and the pores resulting from the hardening and compaction, which, in their entirety, form the pore systems. On account of the partly very irregular and interlinked pores, there is talk about pore distribution and pore geometry. The pore system is, naturally, primarily responsible for the transfer of moisture. The pore size and pore size distribution - thus, finally, the porosity of a material - are the crucial factors for capillary water transfer, water vapour permeability and, naturally, also for the sorption properties. The porosity of materials gives indications on possible water absorption. The higher the porosity of a material is, the lower is the density and the higher is the water absorption of this material. In the foreground is the consideration of the pore structure of a material, which is characterised by the pore volume, the pore size distribution and the so-called pore geometry. (Frossel, 2006, p.26)

Many things depend of pore size. Pores with a radius of less than 10^{-7} m are called microvoids; with a radius smaller than 10^{-9}, they are referred to as gel pores. They are not suited for capillary water absorption and water transfer. Water can only penetrate the pores in the form of water vapour. This means that the materials can be classified as impermeable to capillary water. On one side, they are not able to absorb water through capillary action, for this very reason however, they are not easily impregnated or injected. Pores with a radius between 10^{-7} and 10^{-4} m are referred to as macro- or capillary pores. These pores are suited for capillary water absorption and are able to transfer water and other liquids within the material, in relation to the capillarity. It follows that these materials are not only exposed to capillary water but they may be impregnated or injected without too much trouble. Air voids are pores with a radius of more than 10^{-4} m, thus, already within the millimetre range. These pores are unsuited for capillary water absorption, too. As with macro- or capillary pores, moisture can only be transferred within the air voids in the form of gaseous water vapor or under pressure, in the liquid form. Different pore diameters in mineral material can be seen in figure 2.1.

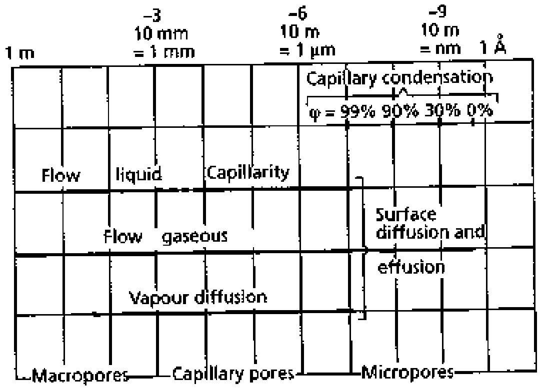

Figure 2.1 Depiction of the different pore diameters in mineral material (Frossel, 2006, p.27)

When considering the pore systems, some further differentiations need to be made between closed and open pores and between continuous and so-called sack voids. With cement-bound materials, there is an additional differentiation to be made between ordinary and artificial air voids. Artificial air voids produce an improved hardened concrete. The pore volume alone is, however, not sufficient to characterise the porosity of a material. The pore size distribution is one of the main characteristics that enables a statement of the moisture transfer. The same pore volume of two different materials may be distributed over many small or a few big pores. Here, microvoids and macropores are to be distinguished. Through capillary condensation, pores with a radius of 10^{-7} m can still be filled with water. This is why this value is often used as limiting pore radius, to differentiate microvoids and macropores.(Frossel, 2006, p.27)

A further characteristic property is the pore geometry. Pores may be arranged cylindrically, wedge-shaped, slot shaped or spherically. They may be more or less connected with each other, so that open pores with at least two openings, sack pores with at least one opening or closed pores without connection with the surroundings. Different pore types can be seen in figure 2.2

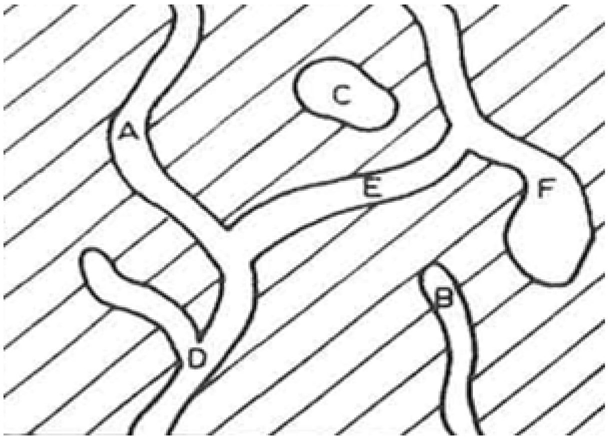

Figure 2.2 Different pore types: A-continuous pore, B-open pore, C-closed pore, D+F - sack pore (Frossel, 2006, p.28)

Only sack pores and open pores are relevant for the moisture balance because water penetrates only via these pore types. Comparing different materials regarding their void ratio, it can be observed that materials with nearly the same void ratio still have very different thermal and hygric properties. The reason is the pore distribution of a material, which, consequentially, is nearly always determined in practice. (Frossel, 2006, p.28)

2.2. Moisture transport processes in masonry walls

The consequences of moisture in masonry are numerous and often very complex. We have possibility to solve problem only when we know exactly what cause problem. In figure 2.3 shown different moisture sources.

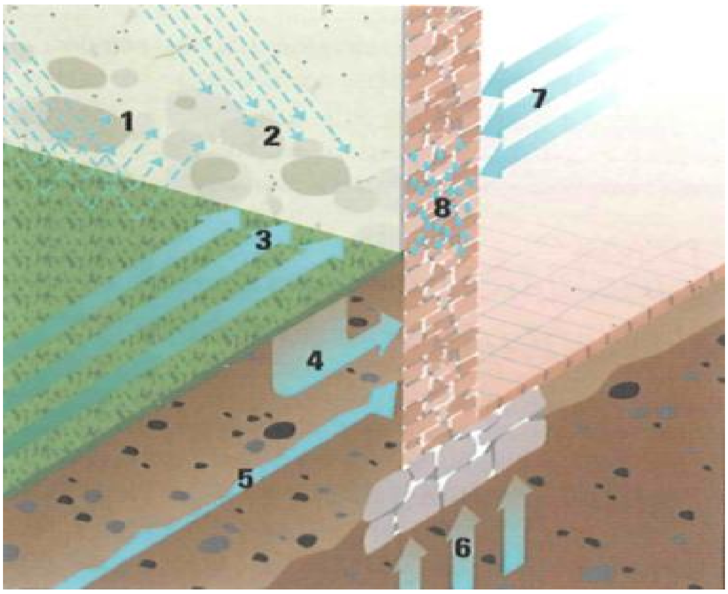

Figure 2.3. Different moisture penetration procedures: 1 - splash water, 2 - wind-driven rain, 3 - surface water, 4 - seeping water, 5 - stratum water, 6 - elevation of ground water, 7 - condensation and 8 - hygroscopic humidity (Frossel, 2006, p.34)

The main causes of moisture movement in masonry are vapour diffusion, surface diffusion and capillary conductivity. Considering a capillary in the masonry, under wintry conditions, a higher temperature can be found on the inside, and thus, also a higher vapour pressure than on the outside. Due to the higher outdoor air humidity, the gradient of the relative humidity or the water content runs contrary to it. If the structural component is dry, then the vapour diffusion in the considered capillary only happens from the inside out; the water sorbed in the walls stays immobile because of high adhesive forces. If the dampness increases generally, a sorption layer is formed on the pore wall, which is thicker outside than inside because of the higher relative humidity. The higher, however, the film thickness, the more mobile the water molecules become, moving from areas of higher film thicknesses to areas of lower film thicknesses. This process is called surface diffusion. Its expanding gradient is the capillary subpressure, or rather, the relative humidity. Surface diffusion, as well as capillary conductivity is, thus, part of the liquid transport and not vapour diffusion, as often assumed. With surface diffusion, as opposed to vapour diffusion, the moisture transported from the inside out is diminished in the capillary under consideration. In case of a further increase in total moisture through capillarity, it is even reversed. (Frossel, 2006,p.34)

Because problems associated with moisture and/or subsequently appearing damages to structures usually occur in the base area, on basement interior walls, they are often solely associated with rising damp in the masonry. There are a number of further mechanisms that increase the moisture content in a wall:

- capillary water absorption
- water absorption through seepage water or slope water in earth-contacting areas
- hygroscopic water absorption
- water absorption through condensation and capillary condensation.

Water absorption mechanisms means that moisture is absorbed due to the absorbing capacity of the material, the moisture absorption in the other cases happens from the gas phase. For this reason, the water absorption can, initially, not be optically observed. Consequently, these moisture mechanisms are often underestimated and the significance is only noticed once the damage has occurred.(Frossel, 2006,p.35)

The most significant water absorption mechanism for the moisture transport in structures - capillarity or capillary conductivity - needs to be considered first. The capillary effects that move water in the tight pores of a material can be attributed to the intermolecular interaction of forces. Attractive forces act between the units of the solid and liquid matters that also, amongst other things, hold them together. These forces, acting between the moleculars of a phase, are called cohesion forces. Interaction forces also occur in the dividing layer between the different phases. These are referred to as adhesion forces and act between the molecules of the mineral material surface and the pore water. (Frossel, 2006,p.35)

Materials always take up water through capillary action, when they are in direct contact with moisture. This happens mainly in facade and earth-contacting areas. Because, normally, moisture penetration and drying processes alternate in the facade area, a kind of equilibrium moisture forms between the absorbed and the desorbed moisture. If the horizontal damp-proofing course is non-existent or has rotten in the meantime and has become ineffective, the earth-contacting area is permanently soaked and the drying process does not take place. Inevitably, the moisture penetration increases and moisture penetrates the whole masonry through capillary action. (Frossel, 2006, p.35)

Rising damp is a known phenomenon from vegetation. Water rises from the roots up to the leaves in the narrow capillaries of the plant, without any external pressure being applied. Something similar happens with porous building materials, when the existing masonry wall fulfils certain conditions. Water from the surrounding earth is absorbed via the fine capillaries in the masonry wall (Figure 2.4)

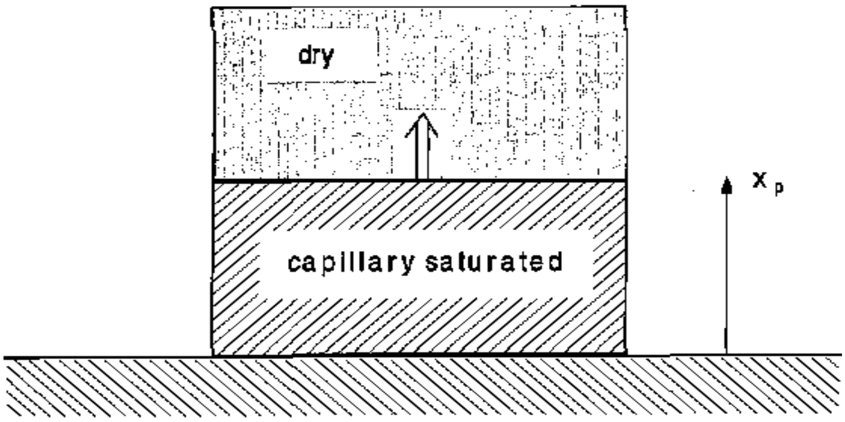

Figure 2.4: Suction of water into a dry material (Hagentoft, 2001, p.101)

Following capillary water absorption, large amounts of moisture are transported into the material after a short period of time. In a masonry wall, the capillary absorbing capacity or water absorption is the main transport mechanism for moisture. It is expressed with the water absorption coefficient A ($kg/m^2 \cdot h^{0,5}$) and is basically determined by the capillary radius of the pores. If the capillary radius is relatively small and lies below 10^{-7} m, they can be referred to as micro voids or gel pores, in which capillary water transport cannot take place anymore. These pores only fill with water through the water absorption mechanism of capillary condensation. With pore sizes above 10^{-4} m, capillary water transport does not happen anymore. The pores possess capillary breaking properties and are often called air voids. They are specifically incorporated into some material mixes. The air voids can only be filled under pressure, such as, for example under the influence of seepage water. With pore sizes ranging from 10^{-4} m to 10^{-7} m, the capillarity is developed best. These pores are, therefore, also referred to as capillary pores.(Frossel, 2006, p.36)

The water absorption coefficient usually describes the capillary absorption pace of a material, but is often used as a general measure for the capillary sorption capacity of materials. The height up to which the water can rise depends on the pore radius. Simplistically, the following equation can be used for water in a wettable material:

$$h_{max} = \frac{1{,}49mm}{r} \qquad (1)$$

Where, h_{max}- max. rise in mm; r - capillary radius in mm (Frossel, 2006, p.37)
But using this formula compulsory remember, if:

Capillary radius < 10^{-7} m $\longrightarrow$ absorption pace ~ zero

Capillary radius > 10^{-4} m $\longrightarrow$ maximum possible rise ~ zero

Water is absorbed because of a missing or no longer effective vertical damp proofing on earth-contacting structural members. This moisture absorption takes place as soon as the humid ground comes into contact with the building material. The water absorption can be intensified if the moisture occurs under a certain pressure (e.g. slope water), such as hydrostatic pressure from the ground. (Frossel, 2006, p.37)

The moisture content of a material always depends on the atmospheric moisture present; it is, therefore, referred to as equilibrium moisture. It can rise severely due to embedded water-soluble salts. The rise depends on the hygroscopic properties, thus, the water-binding properties, of the salts. The particularly easily water-soluble nitrate compounds possess the highest hygroscopicity. Strong salinization and corresponding hygroscopic moisture exposure in a masonry wall can fake, so-called, rising damp. Therefore, a moisture profile, as part of an assessment of structural conditions, is used to establish the hygroscopic moisture penetration and the degree of hygroscopic moisture penetration to be able to plan the appropriate restoration. Recognizing hygroscopic moisture damages through visual inspection is problematic. Indications for the presence of such a burden are moisture wreaths with salt efflorescence's on the surface of structural components. (Frossel, 2006,p.38)

Condensate only appears on the wall surface once the temperature falls below the condensation temperature, which is dependent on the relative humidity. Thereby, condensate can already be formed in capillaries with low air humidity. This condensate formation within the capillary system is called capillary condensation and is influenced by the pore radius of the materials. The smaller the pores of a material are, the bigger the proportion of moisture released through capillary condensation. This means that capillary condensation already takes place in very fine capillaries before reaching the saturated vapour pressure and is responsible for the so-called equilibrium moisture in materials. (Frossel, 2006,p.38)

Condensation is addressed too little in connection with water absorption mechanisms, even though structural damages brought about by and made possible by this are not so rare. Depending on the temperature, the air is capable to take up different amounts of water vapour. At every temperature, the air can take up a certain amount of humidity. This amount of humidity is referred to as saturation humidity (E_{sat}). The saturation humidity is only reached exceptionally. The moisture content of the air, thus, lies below the saturation humidity. When multiplying the quotient of the actual moisture content and the saturation humidity by hundred, the value of relative humidity is calculated.

$$RH = \frac{e}{E_{sat}} \times 100\% \qquad (2)$$

The relative humidity, hence, indicates what percentage of the saturation humidity is reached. The higher the air temperature, the higher is the maximum possible moisture content of the air. This again means that with rising temperature, the air is capable to take up larger amounts of humidity. The relative humidity in a room sinks in relation to the temperature increase. Condensate water occurs when a relative humidity of 100% is reached, thus the so-called condensation temperature is exceeded. The excess vapour content of the air is then deposited on material surfaces. Consequently, serious damages due to moisture penetration can arise. Condensation often significantly influences the moisture profile of structures, for example relatively high air humidity negatively influences the drying tendency of a component. (Frossel, 2006,p.39)

Constant condensation on external walls is a sign of insufficient heat-insulating power of the wall. The moisture penetration is potentially intensified with an increase in air humidity, in consequence of the space utilisation (e.g. utility room, sauna, etc.). Suddenly appearing condensation, especially in corners, niches and window reveals are mostly ascribed to changes in air circulation - for instance due to the installation of new windows or a heating system. Faulty ventilation behavior plays an additional part here. Furthermore, when assessing this mechanism, it needs to be taken into consideration that the air and wall temperature in a habitable space or a building can vary considerably. Especially in the area of external walls or building corners, a substantial temperature lapse can be encountered, depending on the existing thermal insulation. Within this so-called thermal bridge, condensation inevitably arises, hence, condensate is formed. Therefore, specifications need to be made on the present room temperature, the corresponding relative humidity and the temperature distribution across the wall area. (Frossel, 2006,p.39)

For capillary porous materials, the embedment of water molecules, as a result of adsorption and capillary condensation, is called water vapour absorption. The consequential water content increases with increasing relative humidity. This is characterised by sorption isotherms (Figure 2.5). Sorption isotherms are material specific curves, showing the correlation between water absorption of a particular material (also depending on the pore size distribution) and the respective prevailing relative humidity. If the actual moisture content corresponds to the value of the sorptionisotherms, the material is in a physical state of equilibrium. If the moisture content lies above this value, wall moisture is present. (Frossel, 2006, p.40)

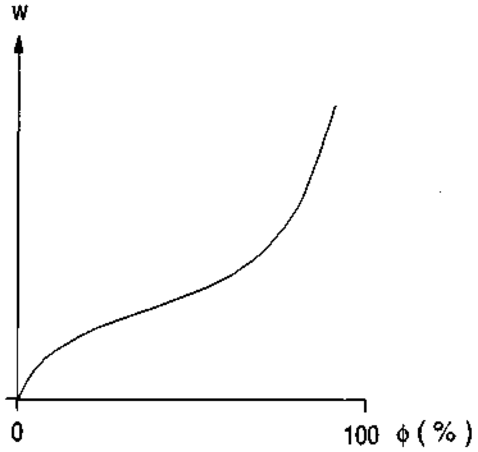

Figure 2.5 Sorption isotherm (Hagentoft, 2001, p.91)

In the low relativity humidity range the water molecules are adsorbed to the pore walls, first in single molecule layers and at higher relative humidities as multilayers. As a next step, capillary condensation will take place. The capacity of storing water in the internal structure of the material increases when this process starts, which can be seen from the increasing slope of the sorption isotherm. More and more pores will be filled with water at increasing relative humidity. The smaller pores will be filled first, and at higher relative humidities also larger pores will be filled.(Hagentoft, 2001, p.91)

There is a limited amount of water that can be stored in a material, captured from the surrounding humid air, at isothermal conditions. This hygroscopic range covers the interval approximately between 0 and 98% relative humidity. A considerable amount of further more water can be fixed to the pore structure, if the material is in contact with liquid water. The upper limit for the moisture content of a material in contact with liquid water is denoted w_{cap} (kg/m^3). Here, cap stands for capillary saturated material. The maximum possible water content of a material, i.e. when all the pores are filled with water, is denoted by w_{sat} (kg/m^3). Here, sat stands for saturated. This level is difficult to reach, since air is easily trapped inside the pores in the material. Figure 2.6. shows the different ranges discussed. (Hagentoft, 2001,p.92)

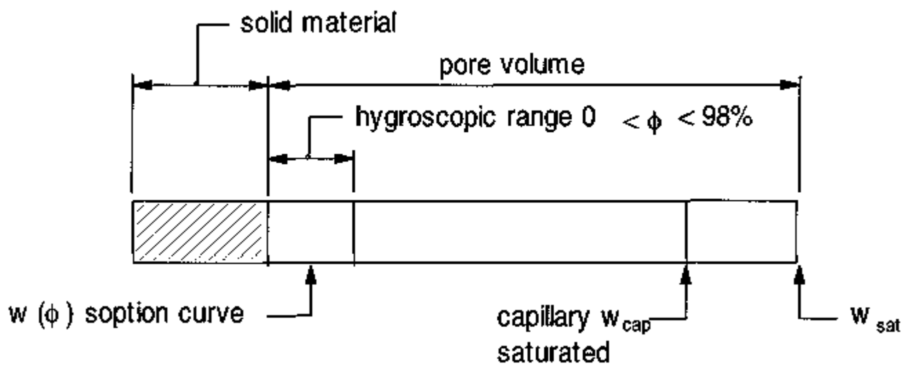

Figure 2.6.: Principle figures explaining the different ranges and the corresponding amounts of water stored in a material (Hagentoft, 2001,p.92)

If a porous building material is soaked in water and allowed to dry in air at different relative humidities it will not retrace the sorption isotherm. Usually, during desorption it retains more moisture than what it can adsorb at any given relative humidity. This phenomenon is referred to as hysteresis, see Figure 2.7.

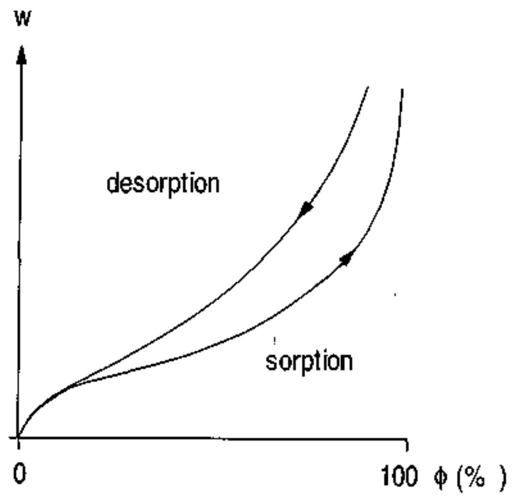

Figure 2.7. Sorption and desorption curve, with hysteresis effect (Hagentoft, 2001,p.92)

Hysteresis shows that moleculs of porouse materials more easily absurbe water then evaporate it back. It can be explained only as nature of materials. Differents between desorption and sorption curves depends only to properties of material and can have variation.

2.3 Materials used in the investigation.

In my thesis work I used materials, which properties can be seen in the table 2.1 All materials were taken from the WUFI 2D database, except injection and sand, which were made by myself, because WUFI 2D does not have that kind of materials. Injection was made by using the recommendation from the WUFI.

Table 2.1: Properties of the materials

Material	property						
	Density [Kg/m^3]	Porosity [-]	Heat. Capacity [J/kgK]	λ_{dry} [W/m k]	μ_{dry} [-]	A-value [kg/m^{2}s$^{1/2}$]	capillary saturation [Kg/m^3]
Solid brick masonry	1900	0,24	850	0,6	10	0,11	190
Lime cement plaster	1900	0,24	850	0,8	19	0,017	210
Rehabilitating plaster	1150	0,6	850	0,13	12,3	0,002	163
Injection	2220	0,05	850	1,6	248	0,00001	40
sand	1570	0,25	850	0,4	8	0,04	157

The water vapour resistance factor, commonly called μ-factor, is therefore a dimensionless number describing how many times better a material or product is at resisting the passage of water vapour, compared with an equivalent thickness of air. Thus high μ-factor means higher resistance to water vapour transmission. Table 1 in Appendix 1 shows some μ-values for different materials. Table 2 in Appendix 1 shows water sorption coefficient (A-value) for different materials.

Storage water in the structure depends of RH, which also influence on the thermal conductivity and water suction and redistribution. WUFI 2D takes into account influence of moisture on the different materials as we can see below in the Figure 2.8. for brick masonry and for other materials can be seen in Figure 1, 2, 3, 4 in Appendix 2, 3, 4, 5, 6, 7.

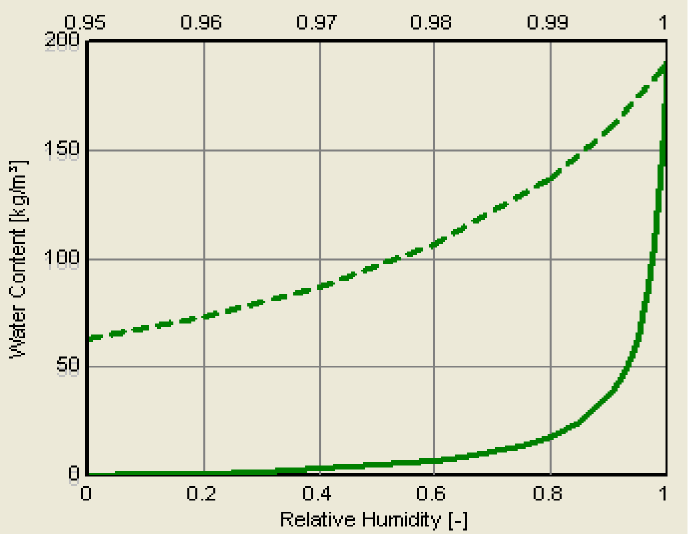

Figure 2.8.1: Moisture storage function for solid brick masonry

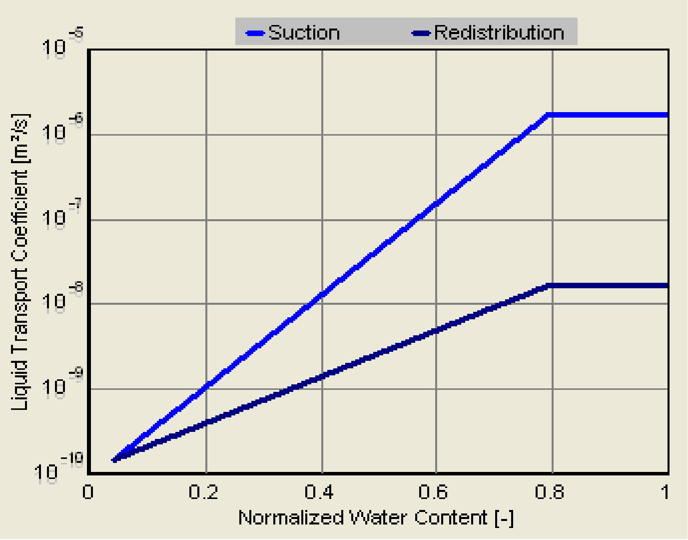

Figure 2.8.2: Liquid transport coefficient for solid brick masonry

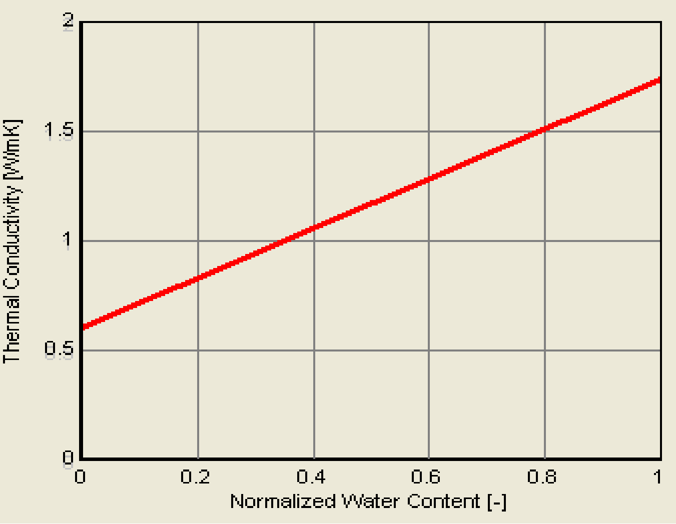

Figure 2.8.3:Thermal conductivity for solid brick masonry

In the above shown figures can be seen dependents between water content and other important values. For instance, if rising water content then increasing RH, increasing velocity of suction and redistribution, increasing thermal conductivity. This mean that wet structure can have large thermal leakages.

Normalized water content, in the liquid transport coefficient curve, show how much water can be within the structure, maximum value is 1 which equal the porosity of the material, hence, for solid brick masonry this value is 240kg/m^3.In the moisture storage function dotted curve show water content which respective relative humidity range from 95% to 100%.

3. MODELLING PROCESS OF CAPILLARY RISING MOISTURE IN BRICK MASONRY.

To explore moisture behaviour in brick masonry wall and the influence of it on rehabilitation methods, we should, foremost, investigate a standard (or a basic) case, so that we can give assessment to rehabilitation methods based on comparison to basic case.

To estimate water content: for starting point was taken the top level of water within the structure, which corresponded to the range of water content between 8 kg/m^3 and 16 kg/m^3, in a basic case and it compares to the top levels of water (water content between 8 kg/m^3 and 16 kg/m^3) in rehabilitation methods, the unit used is centimetre (cm). To estimate relative humidity: for starting point was taken the top level of moisture curve which belongs to range 97-100% in a basic case and it compares to the top level of moisture curve which belongs to range 97-100% in rehabilitation methods. Relative humidity range 97-100% in a basic case, for comparison cases, was taken an equal 100”%”, but this “%” does not mean RH by itself, this “%” expresses only height level of relative humidity.

3.1 Basic case

For our investigation we take the inside wall from brick masonry which has thickness of 420mm, on the surface was used normal lime cement plaster with thickness of 40mm. Water level below floor was one meter. In figure 3.1.can be seen the considered structure with computation scheme where also shown points on which was done measures.

One of the biggest problems was to create a climate file which can model the water level. Because the WUFI 2D doesn't have own data for water. Also the WUFI 2D database doesn't include any soils, that is why it was a necessity to create a new material to apply to reference values for sand.

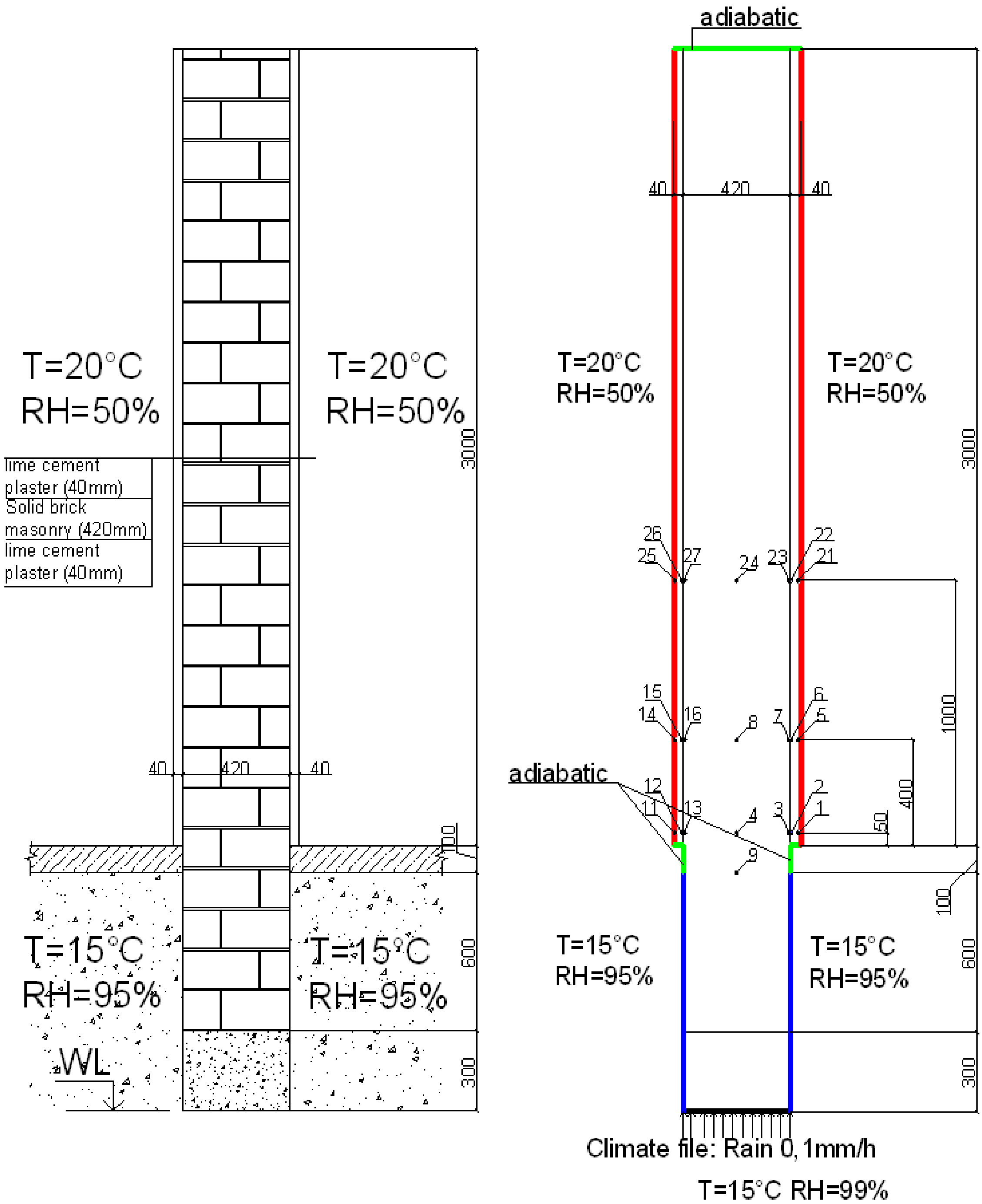

Figure 3.1: Wall structure and computation scheme

Duration of our calculation during which we consider moisture behavior in the wall was 15 years. Preliminary calculations show that 15 years is enough for the structure, so that it stays in equilibrium conditions.

In figure 3.2 is shown fields of water content and relative humidity for a basic case, which demonstrate the possibility of the structure to absorb water.

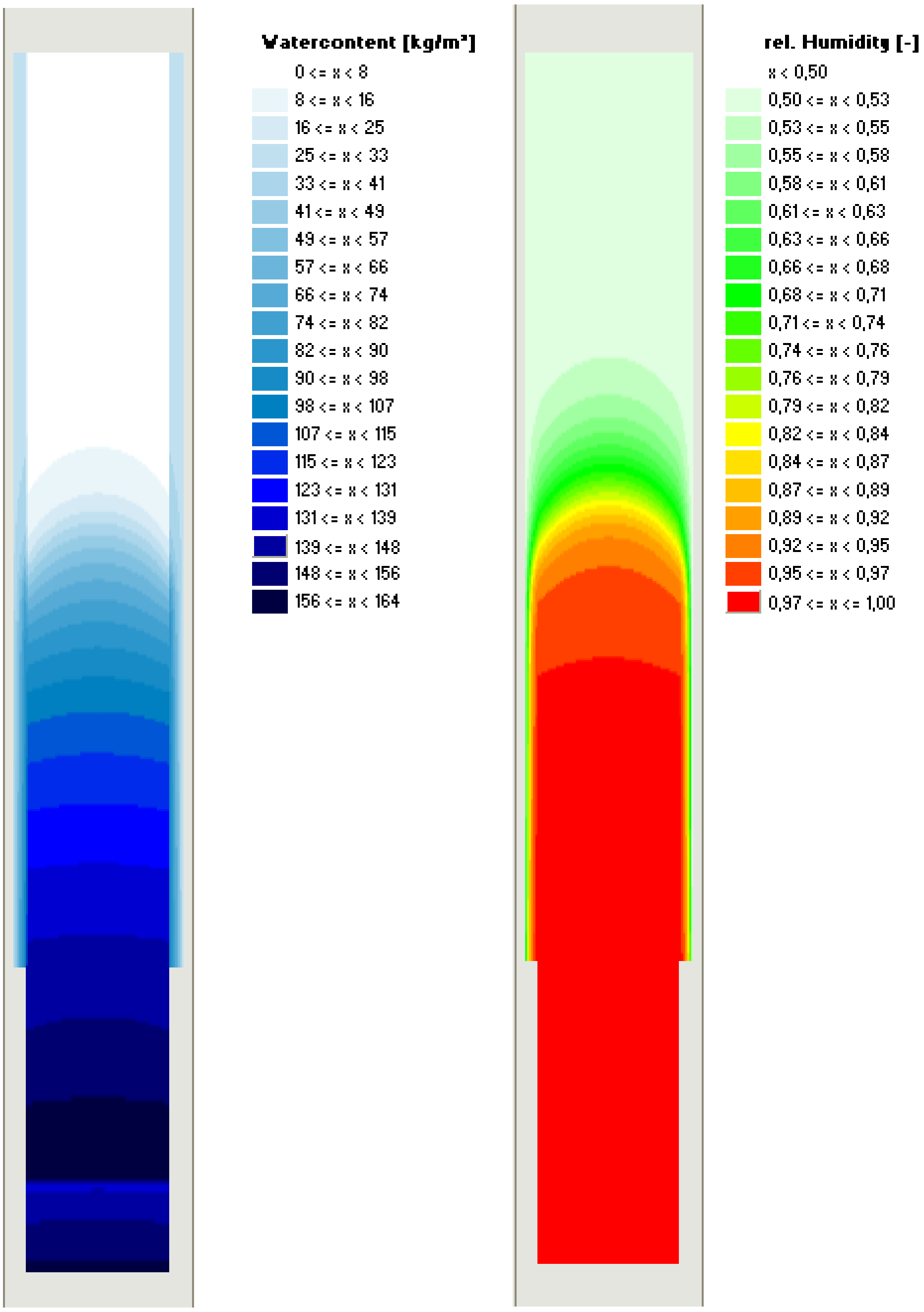

Figure 3.2: Fields of water content (left side) and relative humidity (right side) for a basic case

In the basic case was calculated how much moisture can be absorbed by a normal structure up to 15 years, without using any rehabilitation technologies. The height of water is 172cm over floor level.

3.2. Rehabilitation methods with applying high porosity plasters and vapor proofing layers.

In this part was used rehabilitation methods with applying high porosity plasters and vapor proofing layers. Ambient conditions are the same as in the basic case.

3.2.1. Case with high porosity plasters on both sides.

In this case we put instead of normal lime cement plaster, as in the basic case, high porosity plaster on both sides. Results can be seen in figure 3.3.

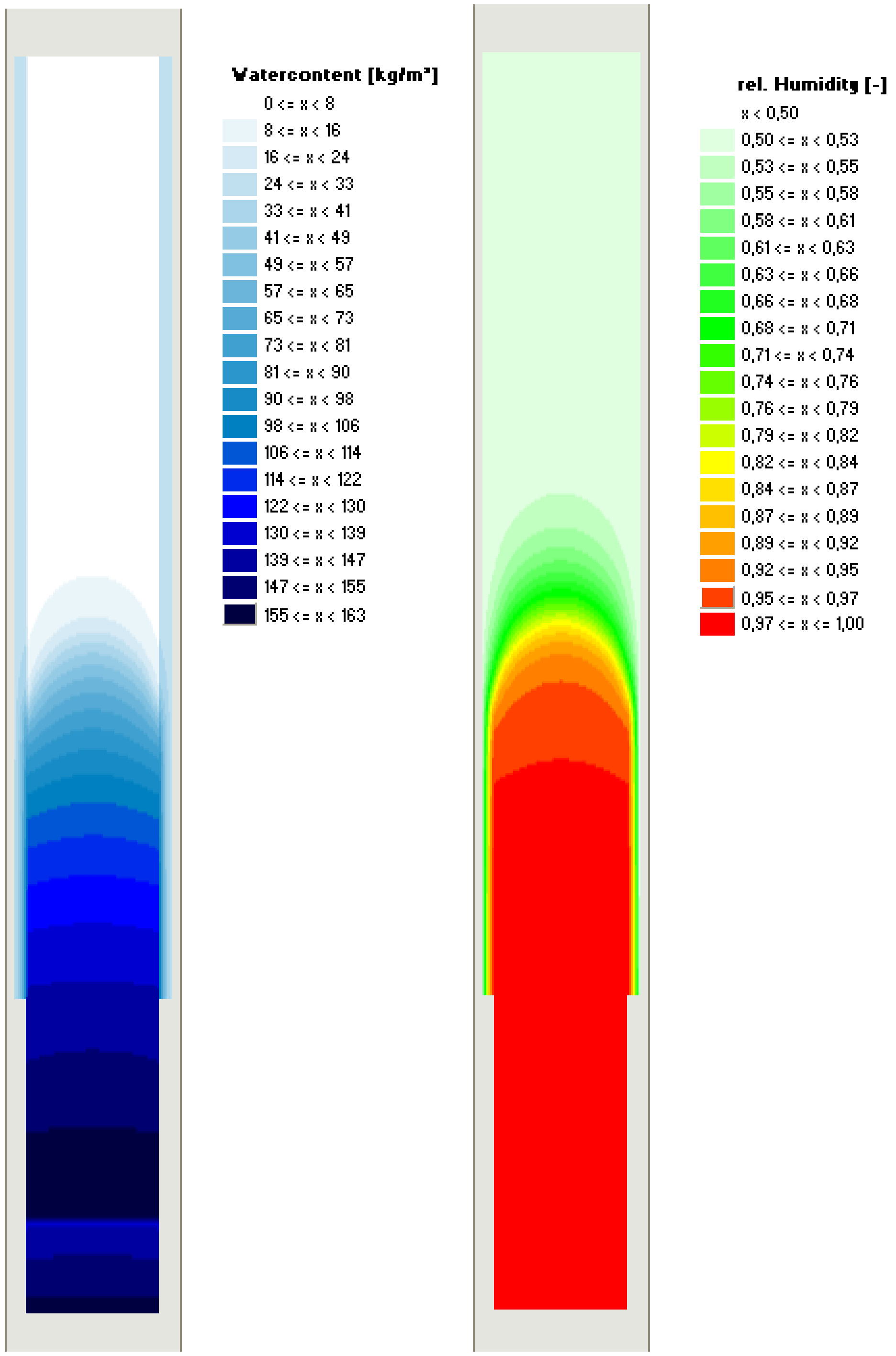

Figure 3.3: Fields of water content (left side) and relative humidity (right side) for case with high porosity plasters on both sides.

In this case height of water is 142cm over floor level. In the basic case level of water was 172cm. Received results mean that applying this rehabilitation method we reduced level of water content to 30 cm, and respectively, relative humidity to 13%.

3.2.2. Case with metal foil and lime cement plaster.

In this case was used instead of normal lime cement plaster, as in the basic case, metal foil on the left side and lime cement plaster on the right side. Results can be seen in figure 3.4. Metal foil was utilized as vapor proofing material with S_d=10000 mm.

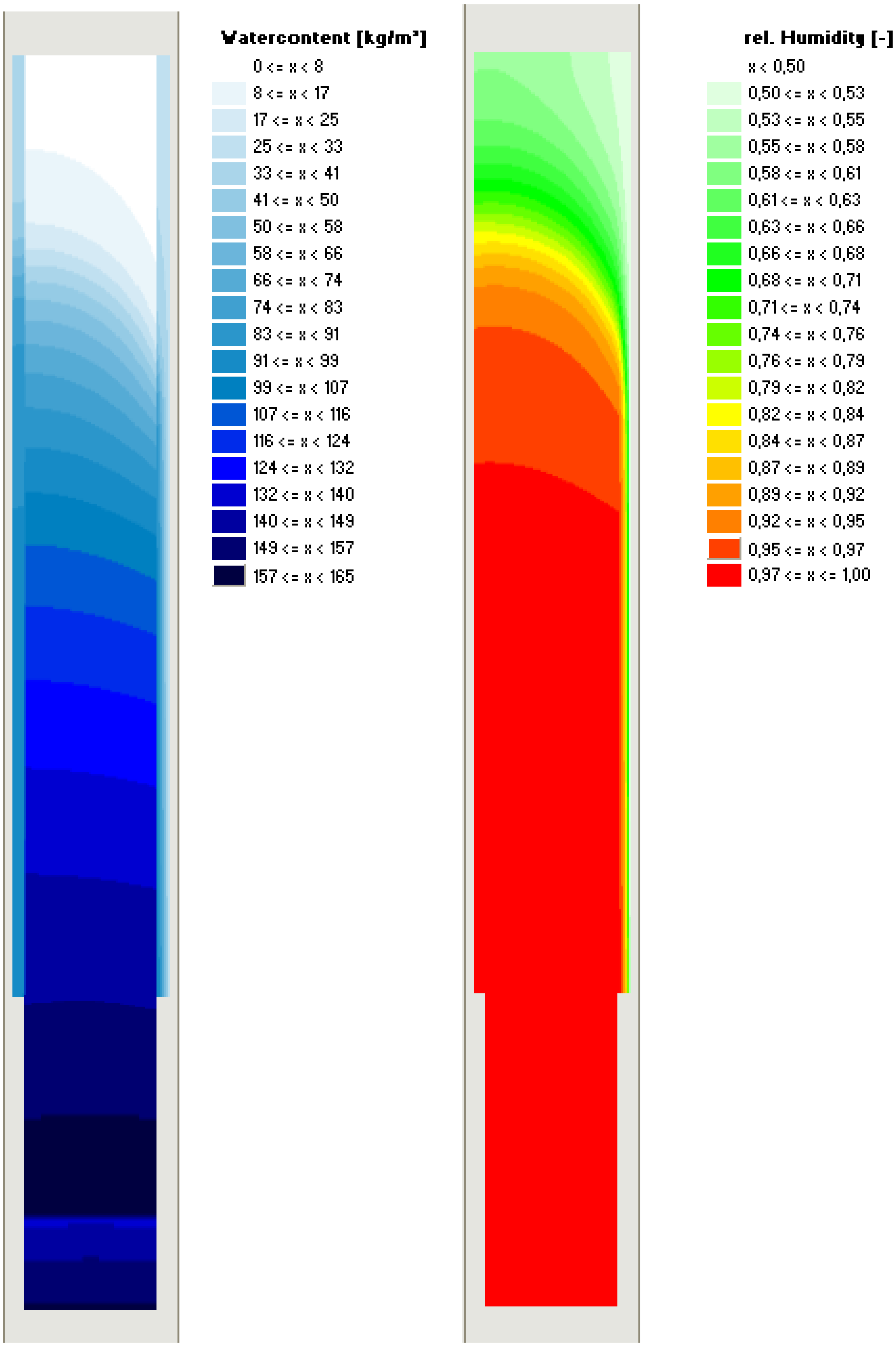

Figure 3.4: Fields of water content (left side) and relative humidity (right side) for case with metal foil and normal lime cement plaster.

In this case height of water is 274cm over floor level. In the basic case level of water was 172cm. Received results mean that applying this rehabilitation method we increased level of water content to 102 cm, and respectively, relative humidity to 52%.This occurs because we prevent evaporation from the left surface. This result cannot be recognized as satisfactory.

3.2.3. Case with high porosity plaster and lime cement plaster.

In this case we put normal lime cement plaster on the left side and high porosity plaster on the right side. Results can be seen in figure 3.5.

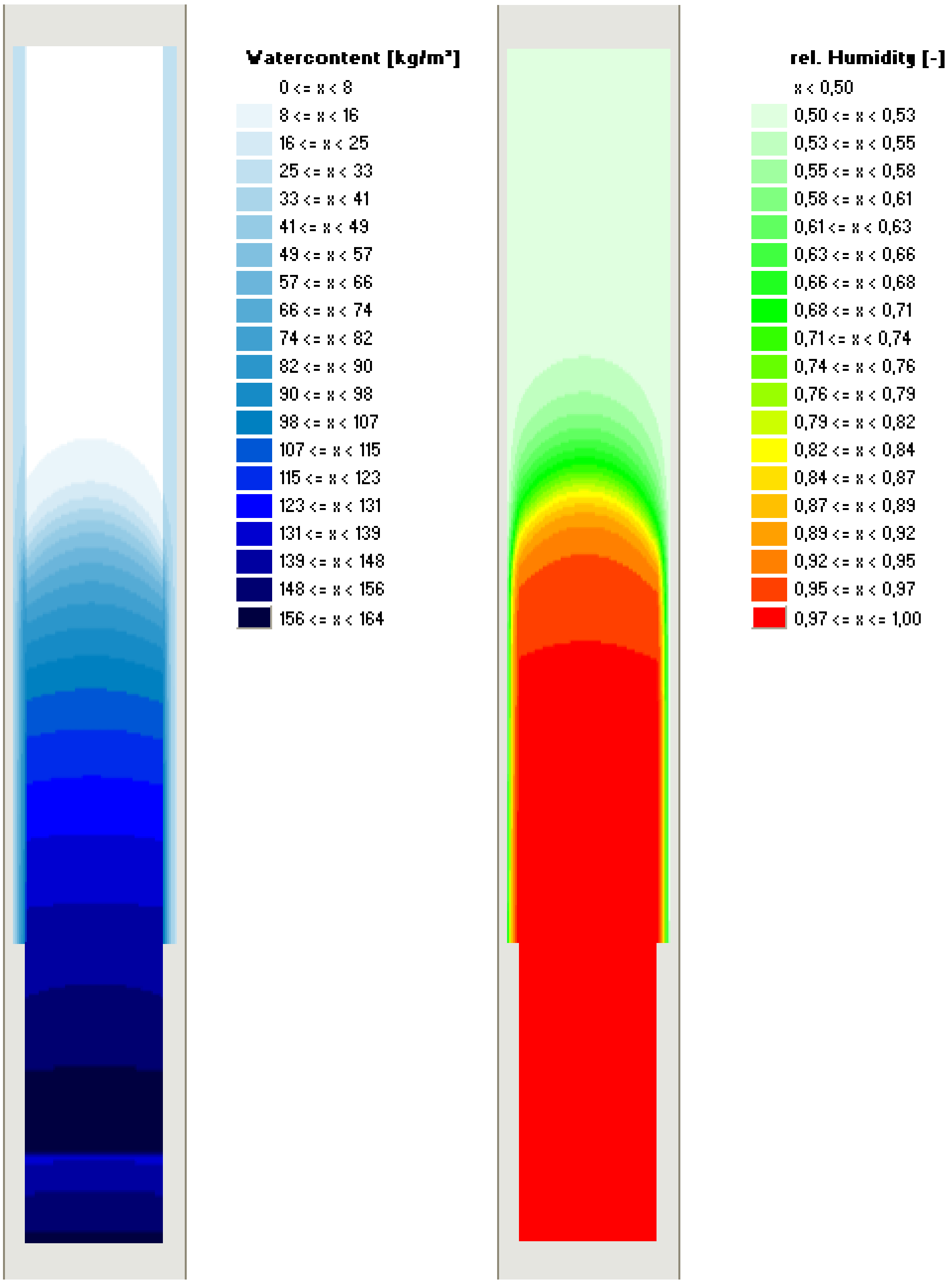

Figure 3.5: Fields of water content (left side) and relative humidity (right side) for case with high porosity plaster and lime cement plaster.

In this case height of water is 170cm over floor level. In the basic case level of water was 172cm.Received results mean that applying this rehabilitation method we have not changed sufficiently the level of water content and the relative humidity. Consequently, this rehabilitation method cannot be recognized as effective.

3.3. Rehabilitation methods with applying injection

The injection was embedded from the right side of the wall in the place conjunction with the floor slab. The thickness of the injection in the wall was 250mm and the height was 40mm. Injection utilized as water repellent material, which prevents absorption of “new” capillary water in the rehabilitation structure. Ambient conditions are the same as in the basic case

3.3.1. Case with injection in a basic case

In this case embedded injection, normal lime cement plaster was used on both sides. Other initial conditions were the same as in the basic case. Properties of the injection are shown in table 2.1. Results can be seen in figure 3.6.

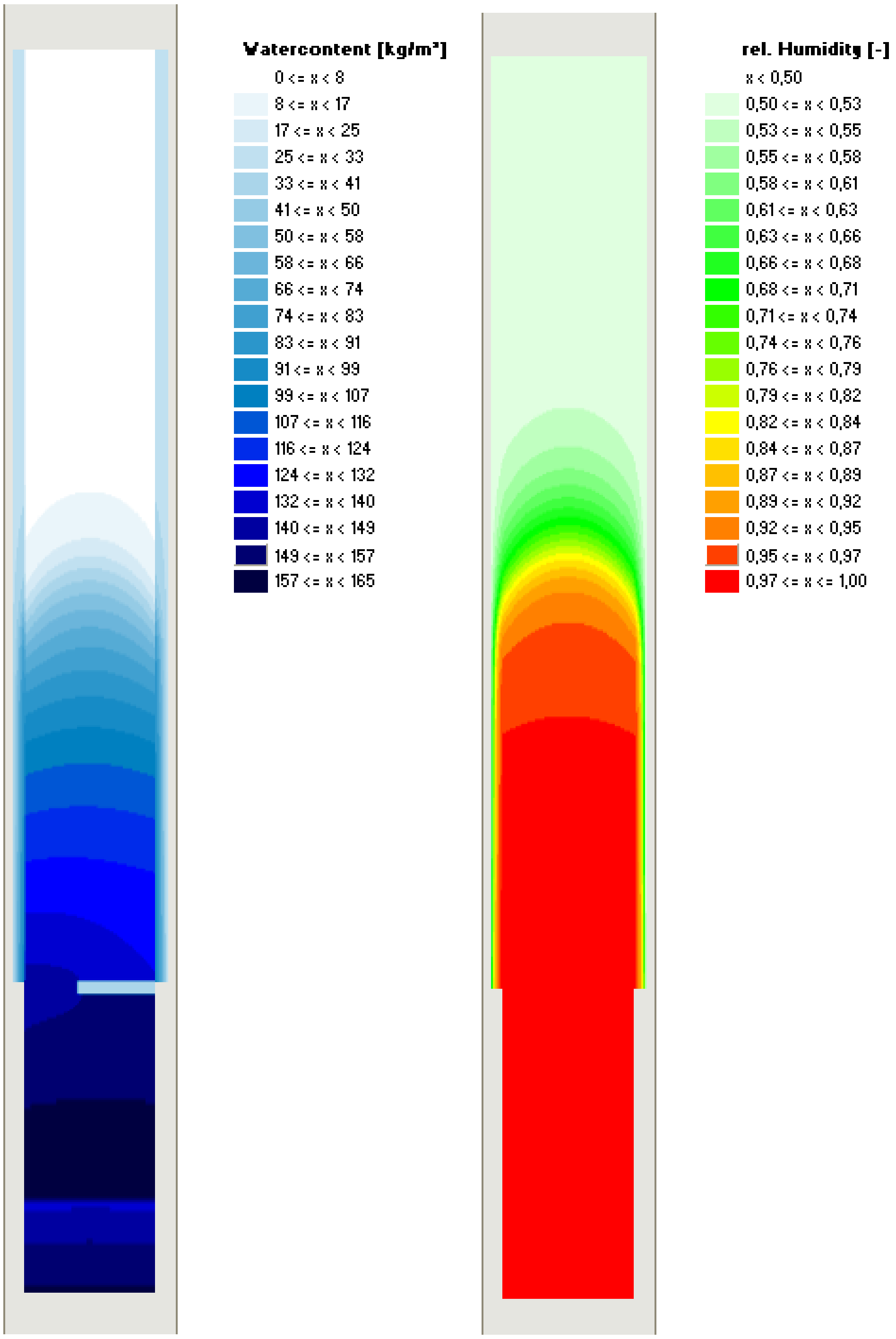

Figure 3.6: Fields of water content (left side) and relative humidity (right side) for case with injection.

In this case height of water is 162cm over floor level. In the basic case level of water was 172cm.Received results show that applying this rehabilitation method we reduced the level of the water content to 10 cm, and respectively, the relative humidity to 7%. This means that applying only one injection for rehabilitation wall is not effective.

3.3.2. Case with injection and high porosity plasters on both sides.

In this case, the injection was embedded and high porosity plaster was put on both sides. Other initial conditions are the same as in the basic case. Results can be seen in figure 3.7.

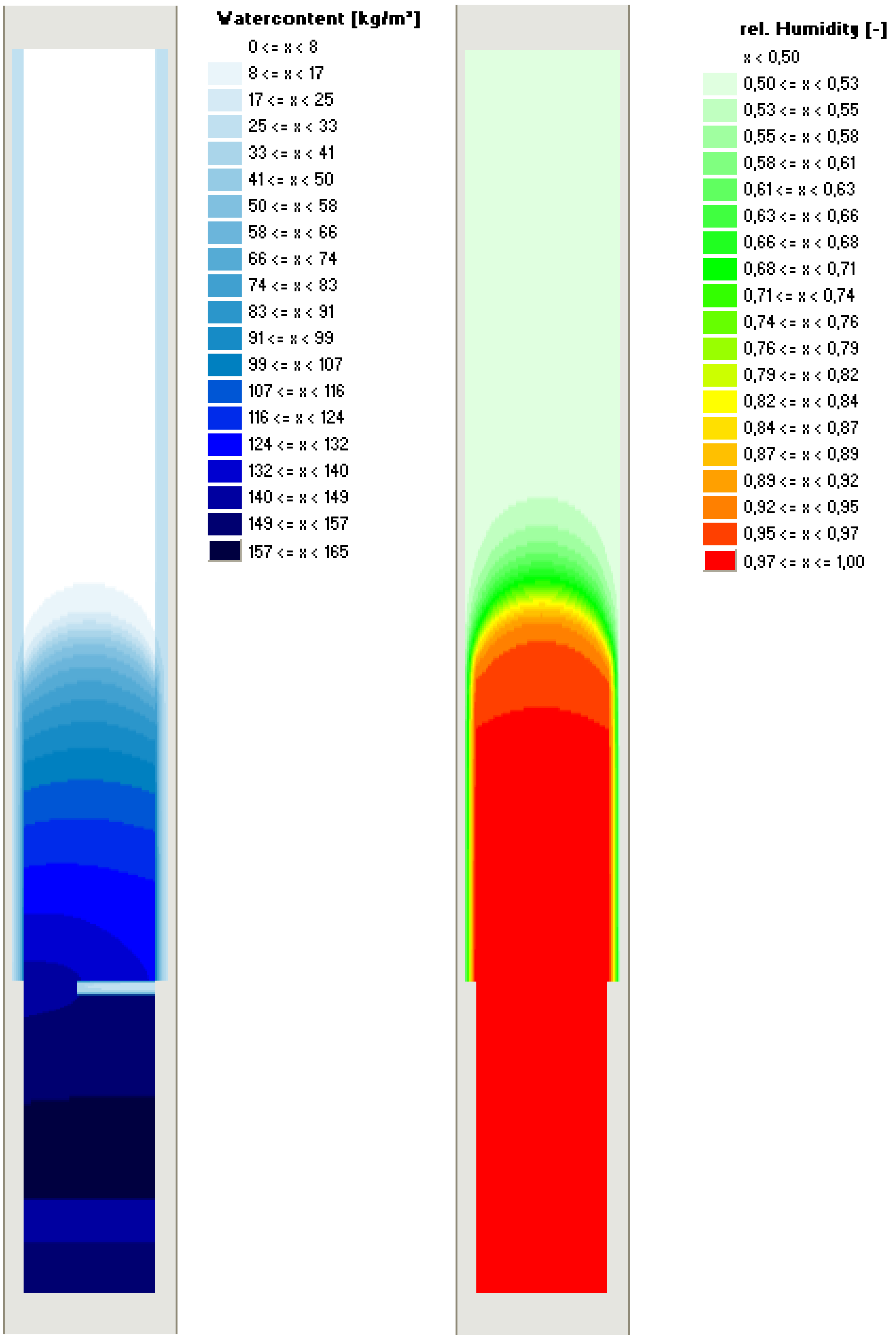

Figure 3.7: Fields of water content (left side) and relative humidity (right side) for the case with injection and high porosity plaster on both sides.

In this case height of water is 132cm over floor level. In the basic case, the level of water was 172cm.Received results mean that applying this rehabilitation method we reduced the level of water content to 40 cm, and respectively, the relative humidity to 15%. This means that applying injection with high porosity plasters for rehabilitation wall is the same effective method.

3.3.3. Case with injection and different plasters

In this case embedded injection was used and normal lime cement plaster was made on the left side and high porosity plaster on the right side. Results can be seen in figure 3.8.

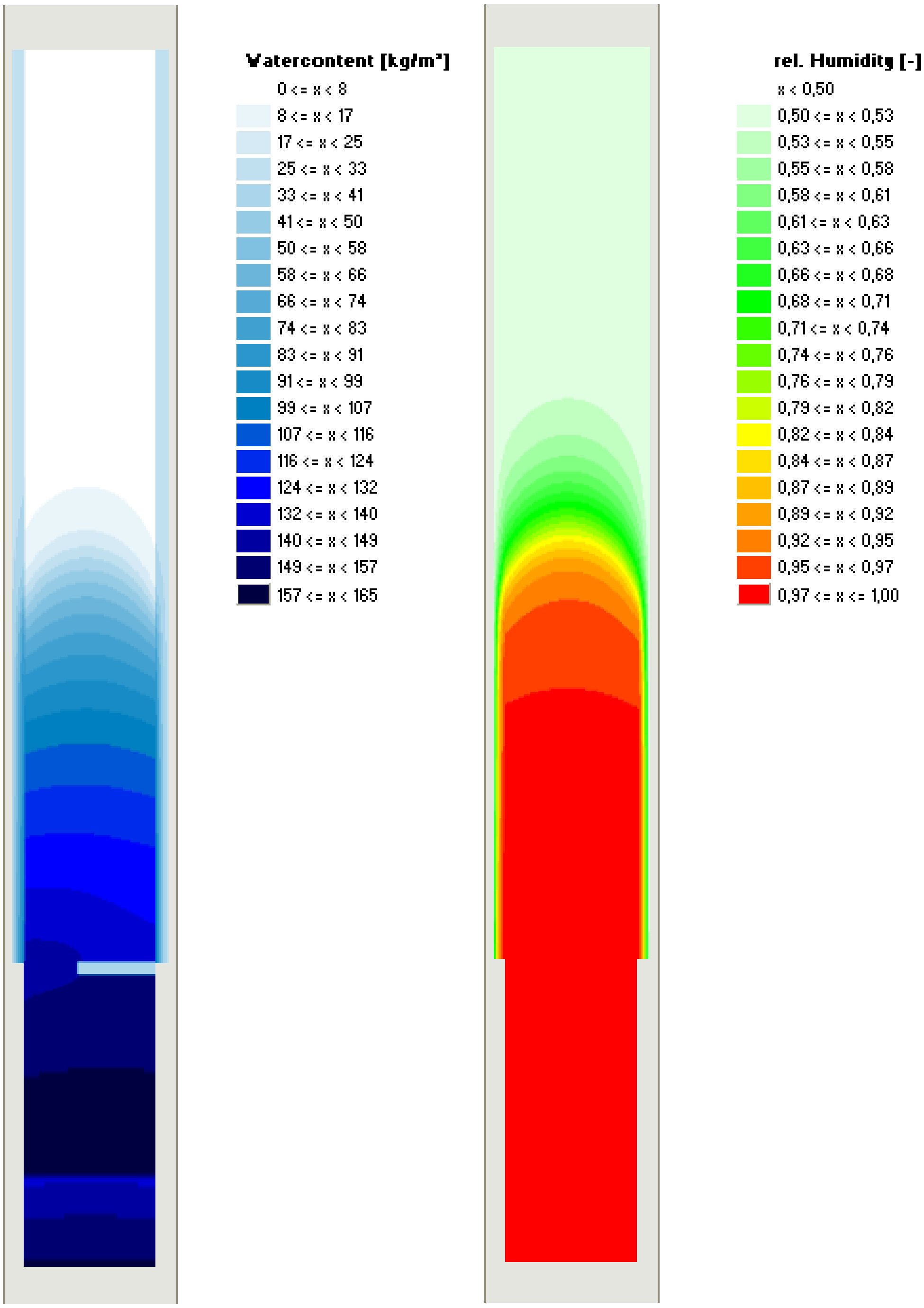

Figure 3.8: Fields of water content (left side) and relative humidity (right side) for the case with injection, high porosity plaster and normal lime cement plaster.

In this case height of water is 155cm over floor level. In the basic case level of water was 172cm. Received results mean that applying this rehabilitation method we reduced level of water content to 17 cm, and respectively, relative humidity to 9%. This means that applying injection with normal lime cement plaster on the left side and high porosity plaster on the right side can be used but will be not as effective as in the previous case.

3.4. Rehabilitation methods with taking into account different temperature and relative humidity.

In this case we consider the influence of different temperatures and relative humidity on the different sides of the structure. Partial pressure (e) was calculated (formula 2) that it will be the same on the different sides. We prevented pressure differences because of diffusion.

3.4.1. Different temperatures (20°C & 10°C) and relative humidity's (50% & 90%) with normal lime cement plaster on both sides.

In this case we use the same structure as in the basic case (on the both sides was normal lime cement plaster), but conditions different. From the left side temperature was 20°C and RH was 50%. From the right side temperature was 10°C and RH was 90%. Results can be seen in figure 3.9.

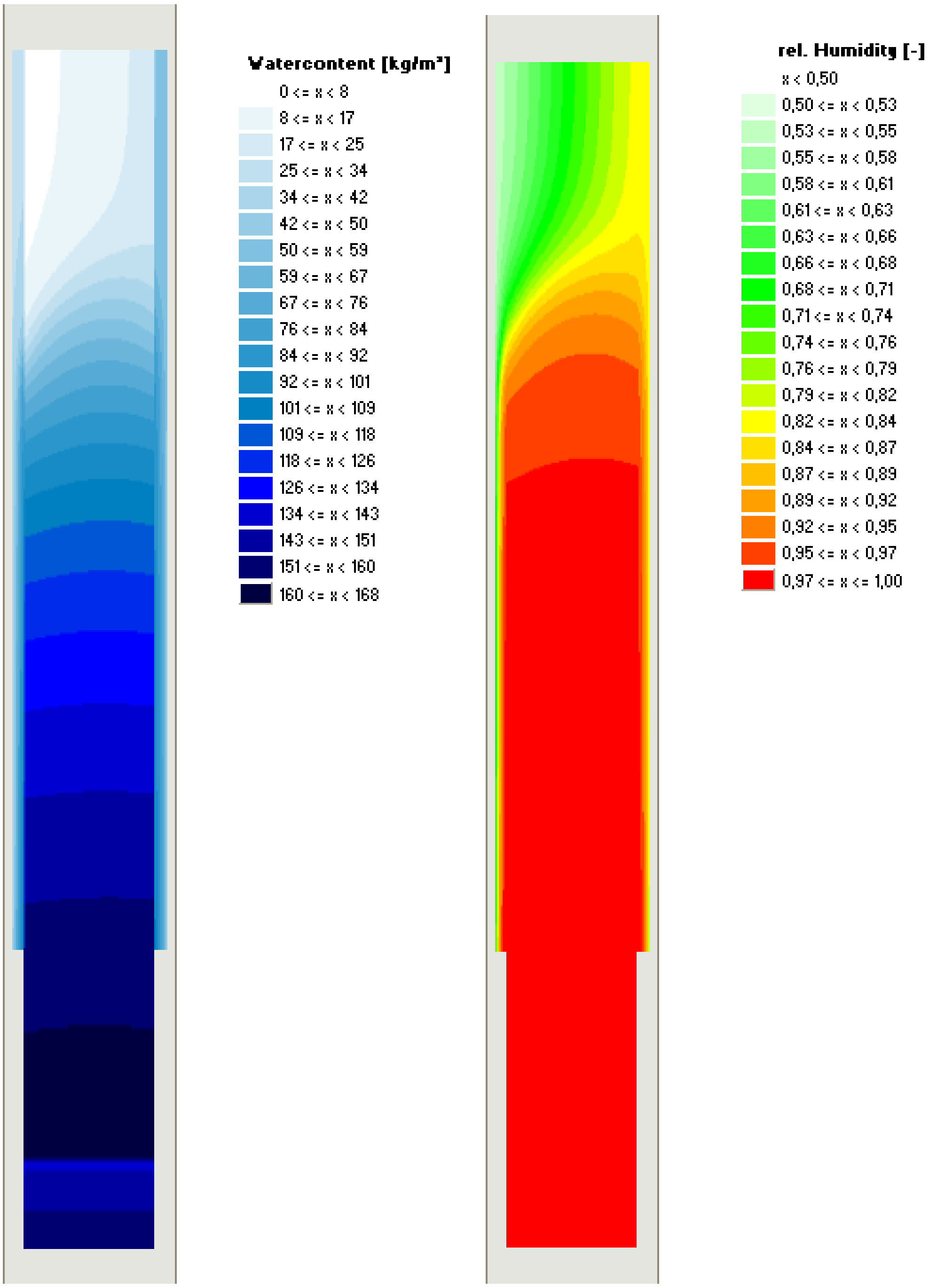

Figure 3.9: Fields of water content (left side) and relative humidity (right side) for the case with different temperatures and relative humidity with normal lime cement plaster on both surfaces.

In this case height of water is 300cm over floor level. In the basic case the level of water was 172cm. Received results mean that the influence of different conditions on the surfaces is significant. We increased the level of water content to 128 cm, and respectively, relative humidity to 67%. Evaporation on the left surface is more rapid because of higher temperature and smaller relative humidity.

3.4.2. Different temperatures(20°C & 10°C) and relative humidities(50% & 90%) with high porosity plaster on both sides.

In this case we use the same structure as in case 3.2.1 (on the both sides was high porosity plaster), but conditions different. On the left side temperature was 20°C and RH 50%. On the right side temperature was 10°C and RH 90%. Results can be seen in figure 3.10.

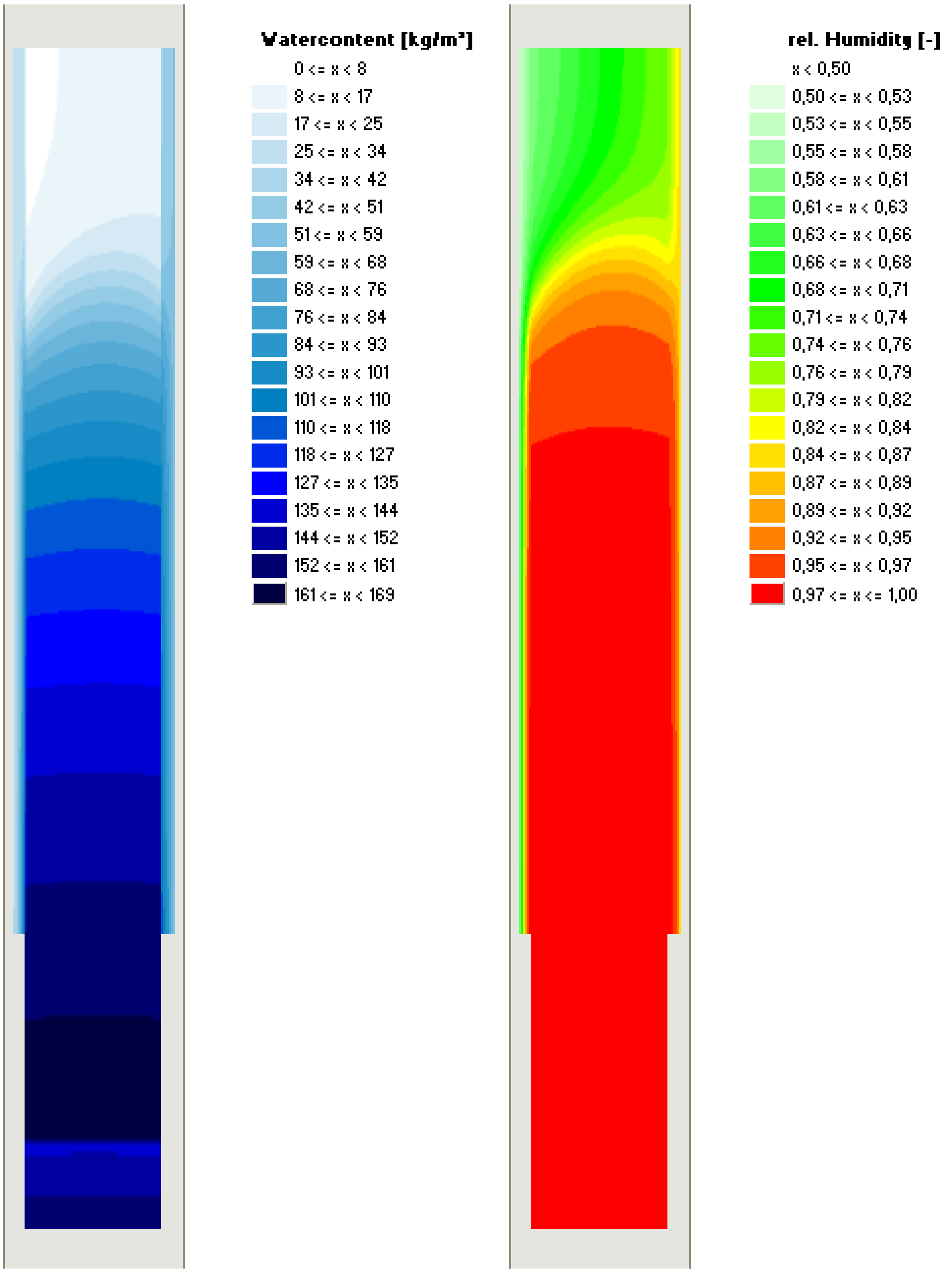

Figure 3.10: Fields of water content (left side) and relative humidity (right side) for the case with different temperatures and relative humidity with high porosity plaster on both surfaces.

In this case height of water is 300cm over floor level. In the basic case level of water was 172cm. Received results mean that influence of different conditions on the surfaces significant. We increased the level of water content to 128 cm, and respectively, relative humidity to 69%. Evaporation from the left surface is more rapid because of higher temperature and smaller relative humidity.

3.4.3. Different temperatures (20°C & 15°C) and relative humidities (50% & 68,5%) with normal lime cement plaster on both sides.

In this case we use the same structure as in basic case (on the both sides was normal lime cement plaster), but conditions are different. On the left side temperature was 20°C and RH was 50%. On the right side temperature was 15°C and RH was 68,5%. RH was calculated specially, so that partial pressure was the same on both sides. Results can be seen in figure 3.11.

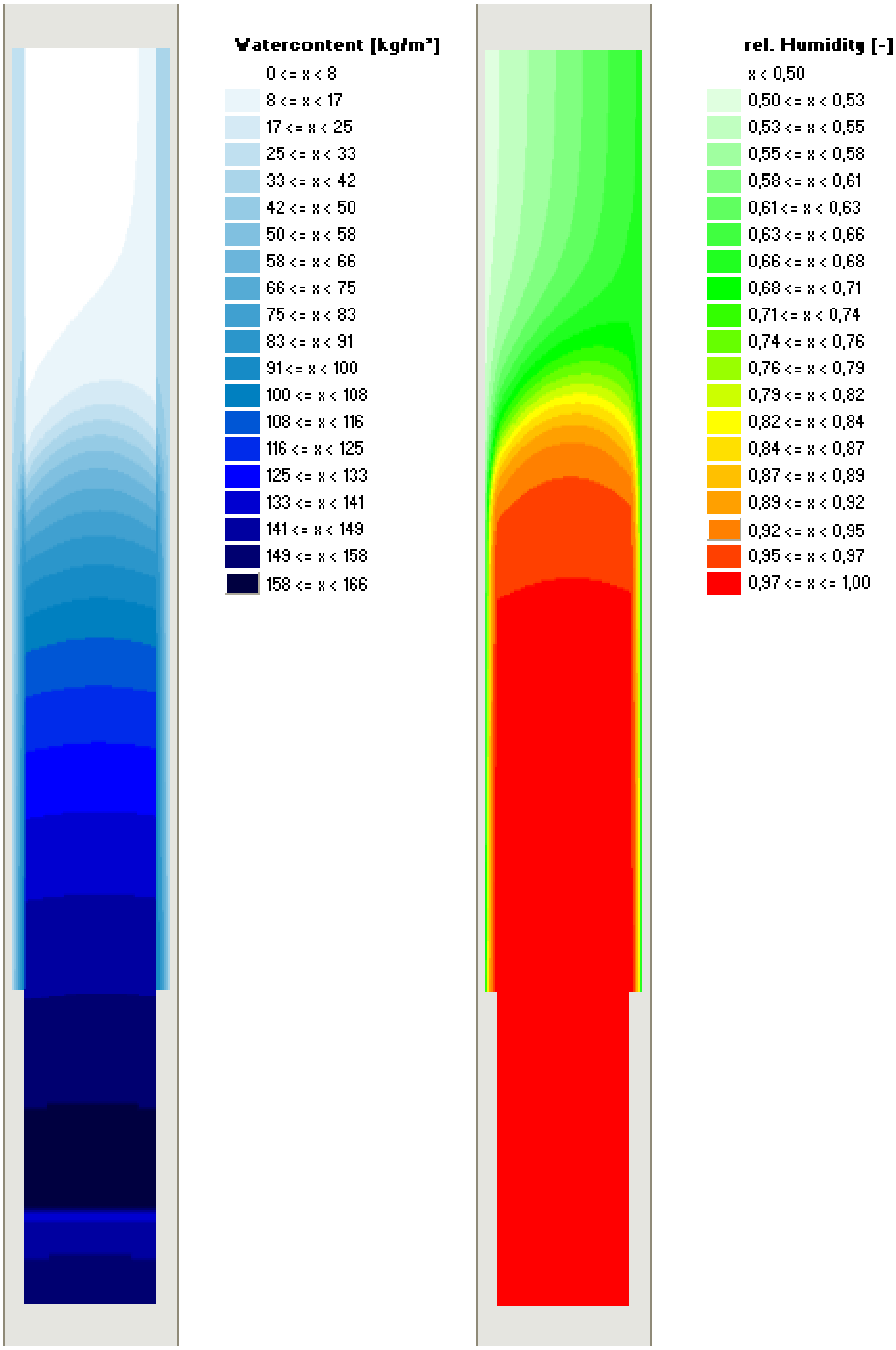

Figure 3.11: Fields of water content (left side) and relative humidity (right side) for the case with different temperatures and relative humidity with normal lime cement plaster on both surfaces.

In this case height of water is 246cm over floor level. In the basic case the level of water was 172cm. Received results mean that when we increase temperature in the colder surface, RH in the structure will drop down. We increased the level of water content to 74 cm, and relative humidity to 32%. The dependents of moisture from RH and temperature can be investigated more exactly, but it was not my target. Evaporation from left surface is more rapid because of higher temperature and smaller relative humidity.

3.4.4. Different temperatures (20°C & 15°C) and relative humidities (50% & 68,5%) with high porosity plaster on both sides.

In this case was used the same structure as in case 3.2.1 (on the both sides was high porosity plaster), but conditions different. On the left side temperature was 20°C and RH was 50%. On the right side temperature was 15°C and RH was 68,5%. Results can be seen in figure 3.12.

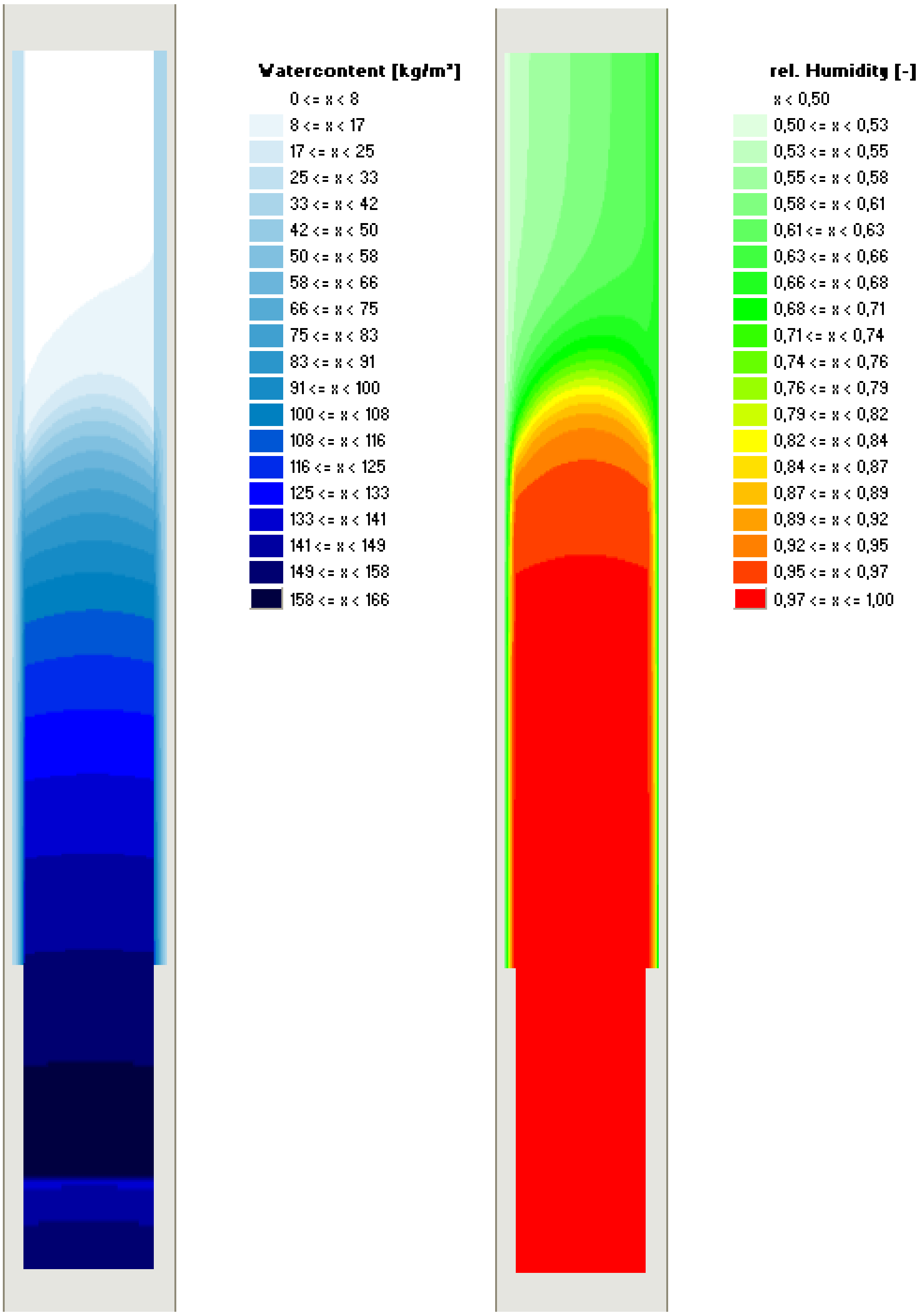

Figure 3.12: Fields of water content (left side) and relative humidity (right side) for the case with different temperatures and relative humidity with high porosity plaster on both surfaces.

In this case the height of water is 251cm over floor level. In the basic case the level of water was 172cm. Received results mean that when we increase temperature in the colder surface RH in the structure will drop down. We increased the level of water content to 79 cm, and respectively, relative humidity to 33%. It shows that structure with normal lime cement plaster contains a little bit smaller water content, when structure with high porosity plaster, if we have temperature differences and constant partial pressure (e).

3.5 Summary

At this part, will be given assessment to all considering rehabilitation methods, it will be achieved by comparison of water content and relative humidity in different points of structure. In Figure 3.1 is shown a basic scheme with points allocation. In Table 3.1 is shown a list of all rehabilitation cases which was used in thesis.

Table 3.1 List of rehabilitation cases

Designation of case	Idea of renovation
3.1 Basic case	-
3.2.1	Case with high porosity plasters on both sides
3.2.2	Case with metal foil on the right side and lime cement plaster on the left side
3.2.3	Case with high porosity plaster on the right side and lime cement plaster on the left side
3.3.1	Case with injection (plasters as in basic case)
3.3.2	Case with injection and high porosity plasters on both sides
3.3.3	Case with injection, lime cement plaster on the left side and high porosity plasters on the right side
3.4.1	Different temperatures (20°C & 10°C) and relative humidities (50% & 90%) with normal lime cement plaster on both sides
3.4.2	Different temperatures (20°C & 10°C) and relative humidities (50% & 90%) with high porosity plaster on both sides
3.4.3	Different temperatures (20°C & 15°C) and relative humidities (50% & 68,5%) with normal lime cement plaster on both sides
3.4.4	Different temperatures (20°C & 15°C) and relative humidities (50% & 68,5%) with high porosity plaster on both sides

Also necessity to say, about rehabilitation methods used with injection. In real life when we use injection, structure has already been in saturated conditions and injection prevent the coming of new moisture. But in my investigations injection was embedded in a totally dry structure. It was done for unification of all cases, but it can give inaccuracy, if we think about real injections technologies.

In chart 3.1 shown water content and relative humidity in point 1 (right side, on the plaster surface, over slab level on 50mm).

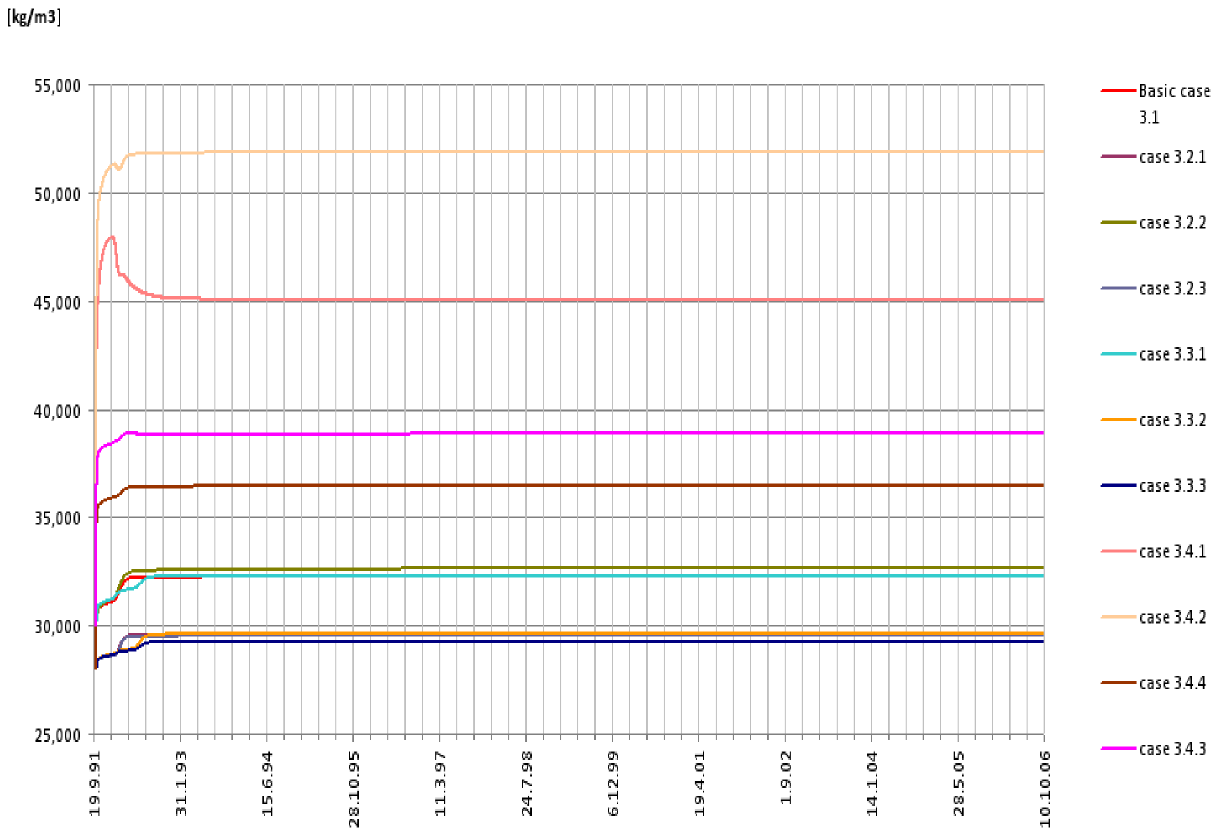

Chart 3.1.1 water content in point 1

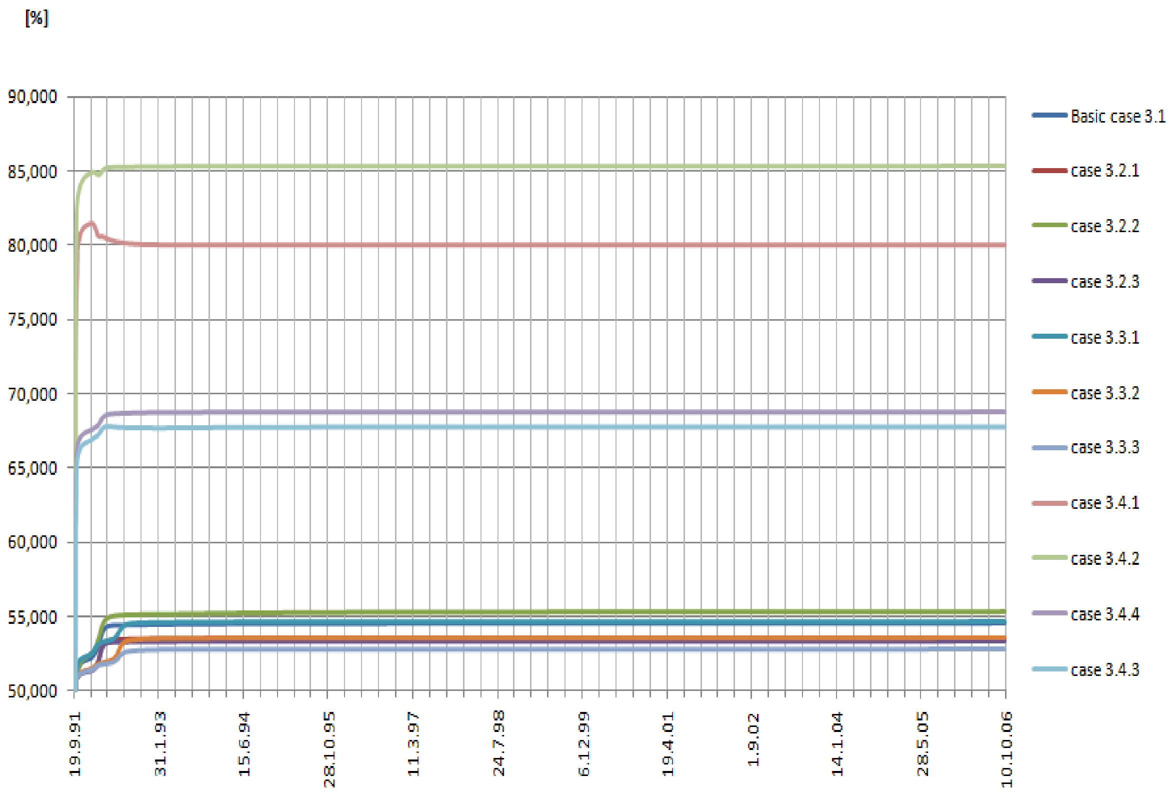

Chart 3.1.2 relative humidity in point 1

As can be seen in the above shown charts: in case 3.4.2. we have the biggest water content 52 kg/m^3 and relative humidity 85,5%. This results show that high porosity plaster shouldn't be applied in the walls with different climatic conditions(T and RH). In the second place case 3.4.1 in which we get water content 45 kg/m^3 and relative humidity 80%. This means that lime cement plaster evaporate water better than high porosity plaster, if we have different climatic conditions on the surfaces. Cases with the same climatic conditions on the surfaces (3.1÷3.3.3) show approximately the same results: water content 28,5÷32,5 kg/m^3 and relative humidity 53÷55%. In surface points 5 and 21 we receive approximately the same results.

In chart 3.2 shown water content and relative humidity in point 3 (right side, on the masonry wall surface, over slab level to 50mm).

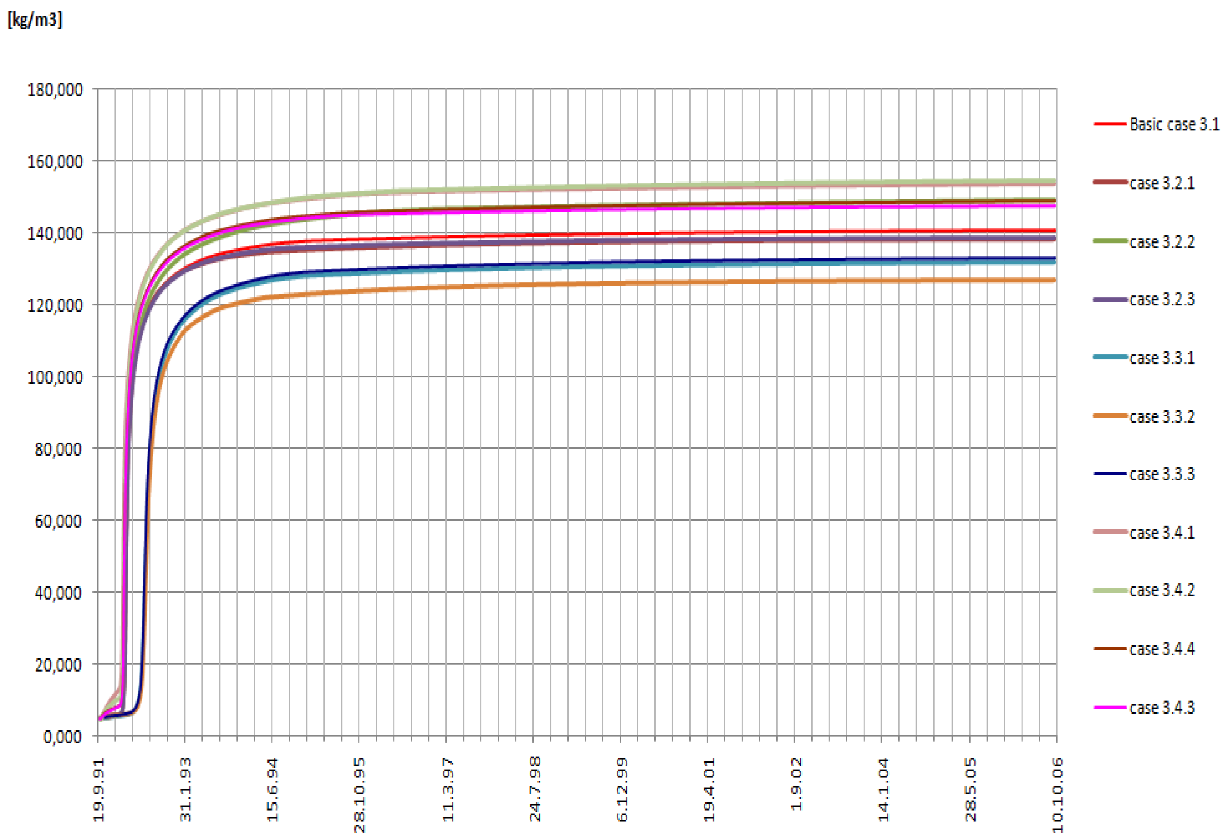

Chart 3.2.1 water content in point 3

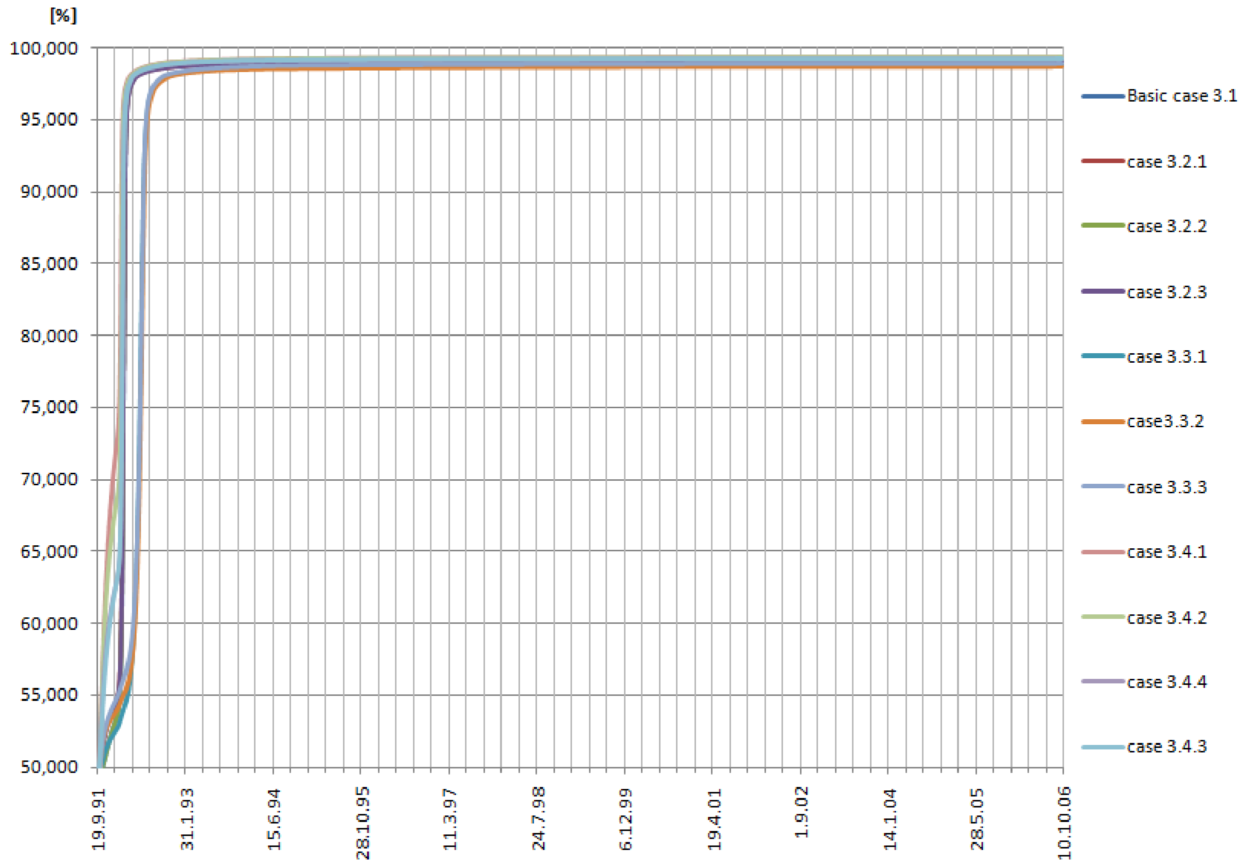

Chart 3.2.2 relative humidity in point 3

As can be seen in the above shown charts: relative humidity in all cases approximately the same (99-100%). The WUFi 2D doesn't show 100% on the chart because of numerical problems that can appear. But water content differs to each other: biggest values in cases 3.4.2 and 3.4.1 152 kg/m^3, the smallest value in case 3.3.2 127 kg/m^3.

In chart 3.3 shown water content in point 7 (right side, on the masonry wall surface, over slab level to 400mm). Relative humidity for all cases have the same values as in point 3 (99-100%).

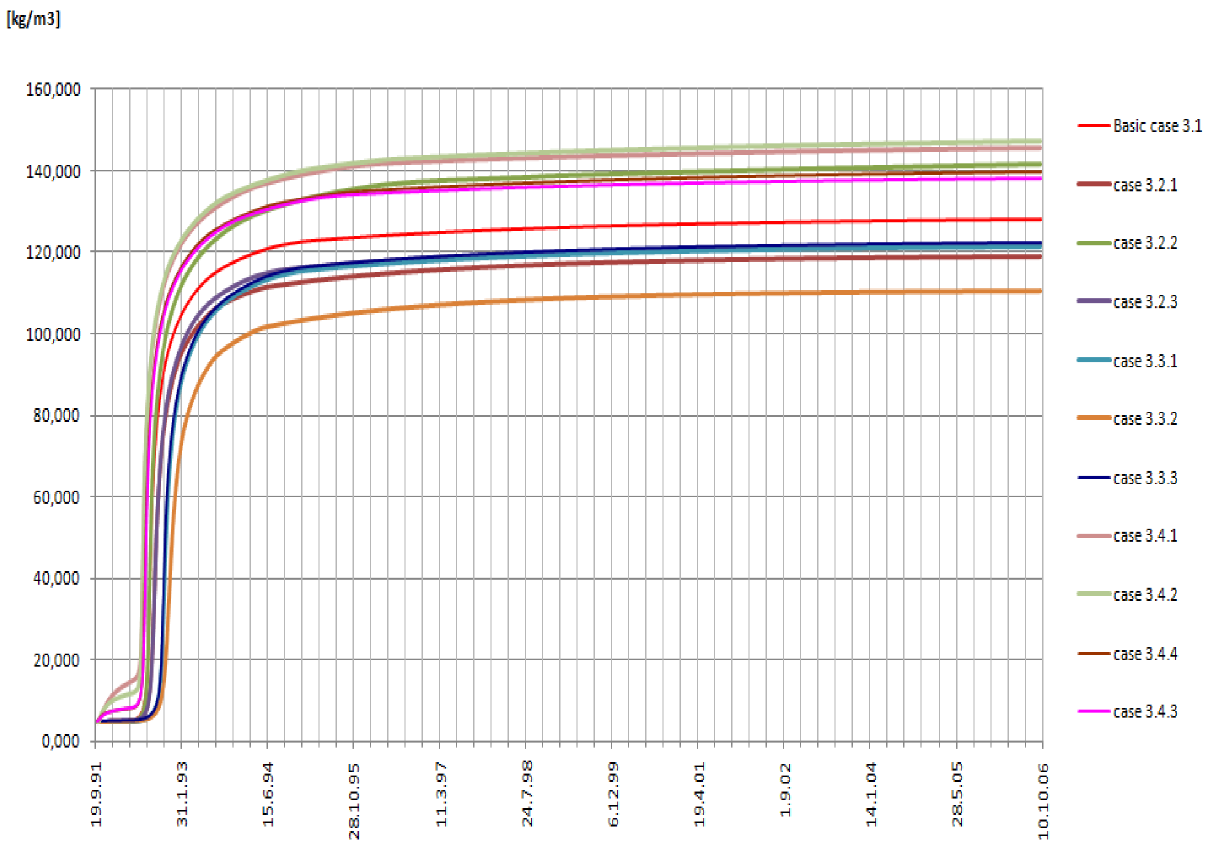

Chart 3.3 water content in point 7

As can be seen in the above shown chart 3.3 water content is smaller than in point 3: biggest values in cases 3.4.2 and 3.4.1 (145 kg/m^3), the smallest value is in case 3.3.2 (110 kg/m^3).

In chart 3.4 shown water content and relative humidity in point 23 (right side, on the masonry wall surface, over slab level to 1000mm).

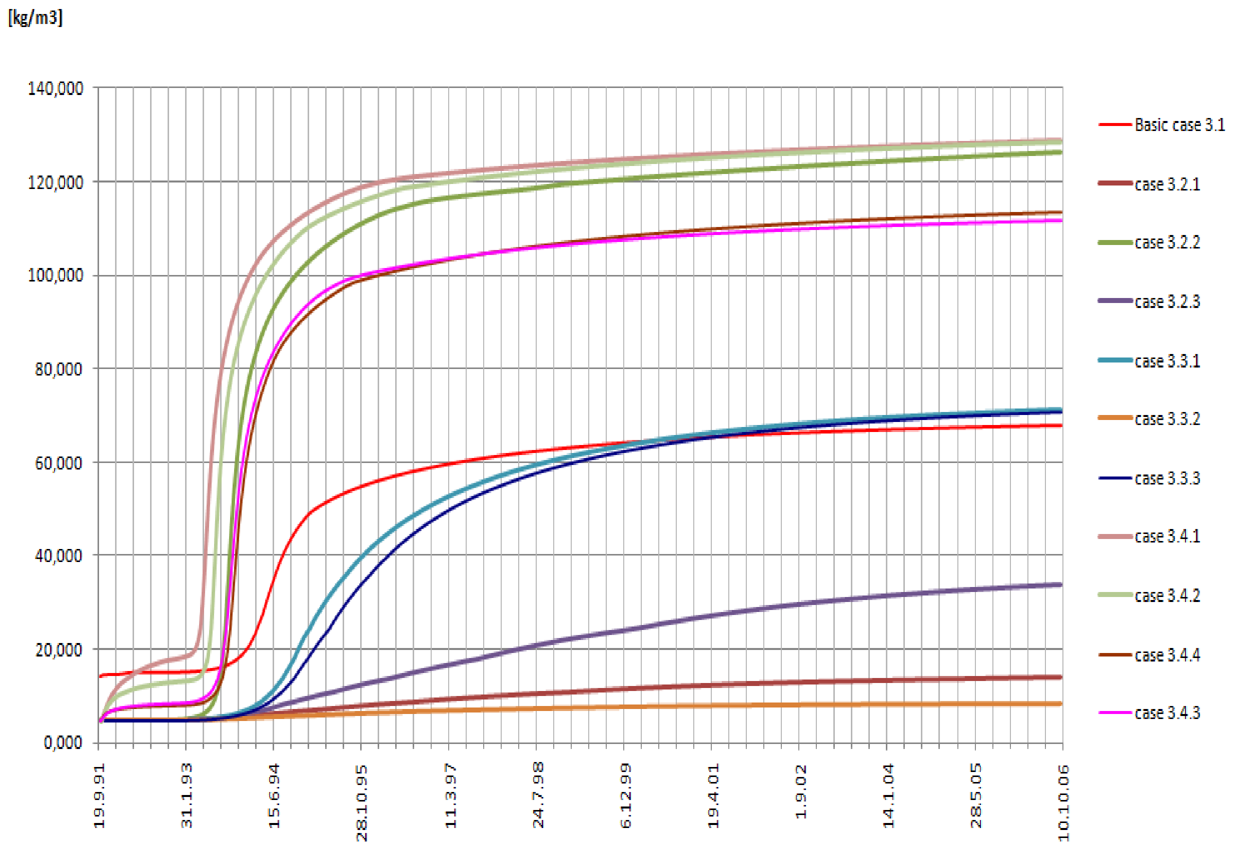

Chart 3.4.1 water content in point 23

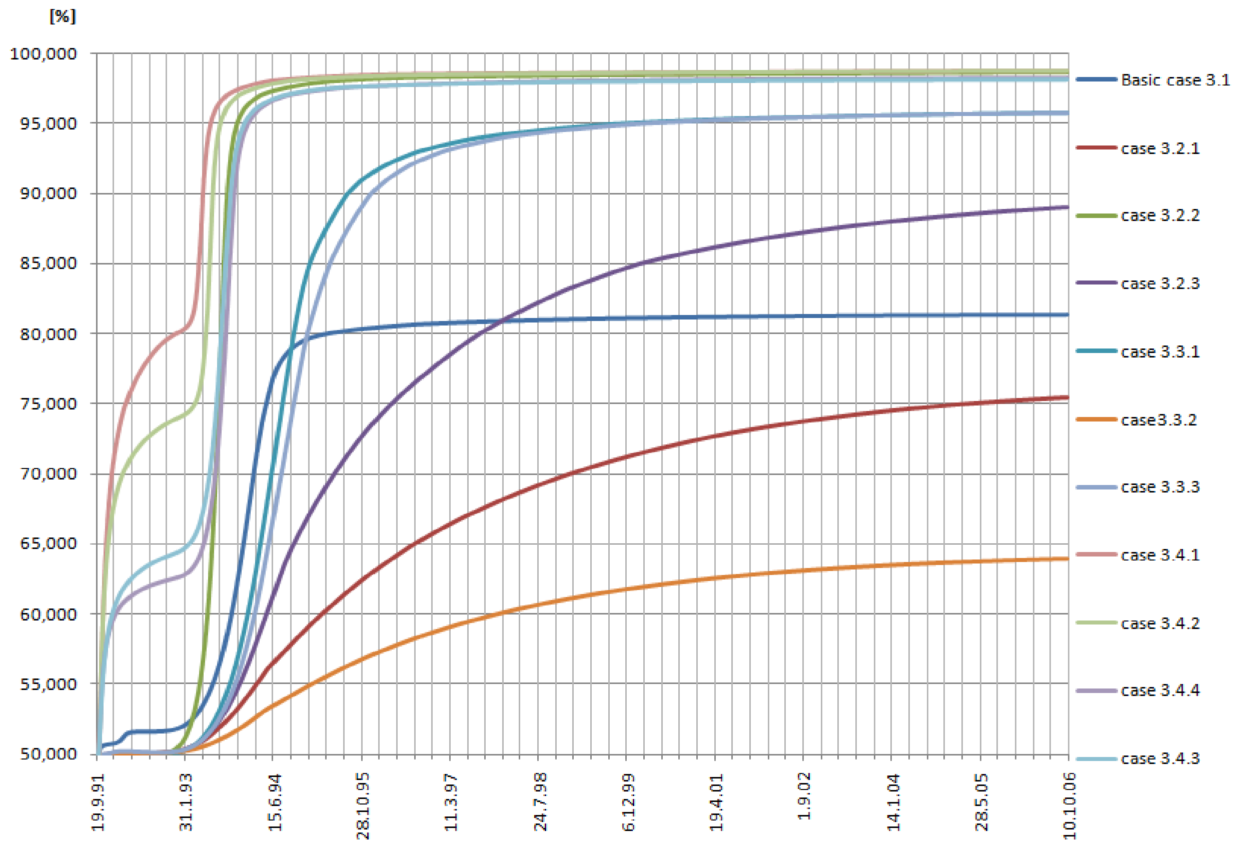

Chart 3.4.2 relative humidity in point 23

As can be seen in the above shown chart 3.4: the biggest water content is as usual in cases 3.4.1 ,3.4.2 and 3.2.2 (123 kg/m^3), the smallest amount of water in case 3.3.2 (10 kg/m^3). Because of this we can see differences in relative humidity: for cases 3.2.2, 3.4.1, 3.4.2, 3.4.3, 3.4.4 it is approximately 100%; for case 3.3.2 it is 64%.

In chart 3.5 shown water content in point 8 (in the middle of masonry wall, over slab level to 400mm). Relative humidity in all cases 100%

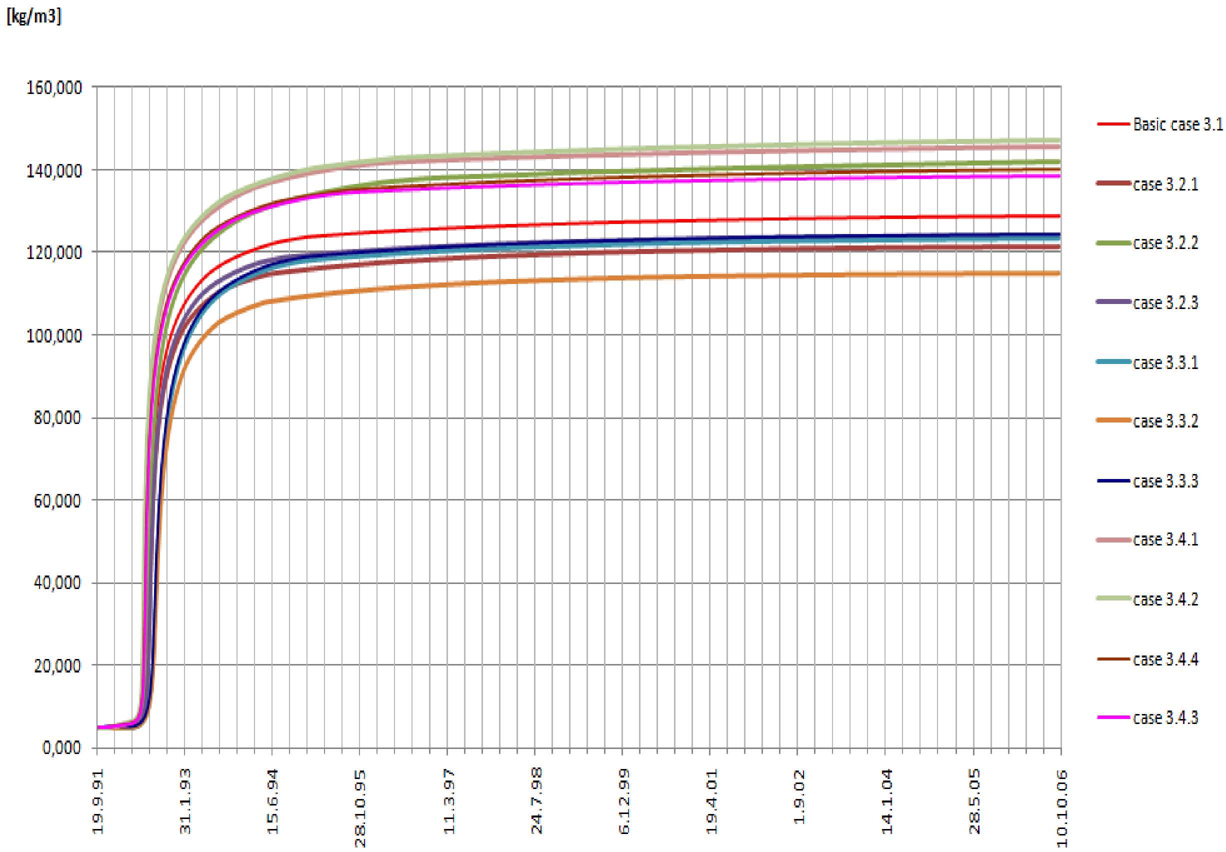

Chart 3.5 water content in point 8

As can be seen in the chart 3.5 water content in the middle of the structure (point 8) is a little bit bigger than on the surface (point 7).

In chart 3.6 shown water content and relative humidity in point 24 (in the middle of masonry wall, over slab level to 1000mm)

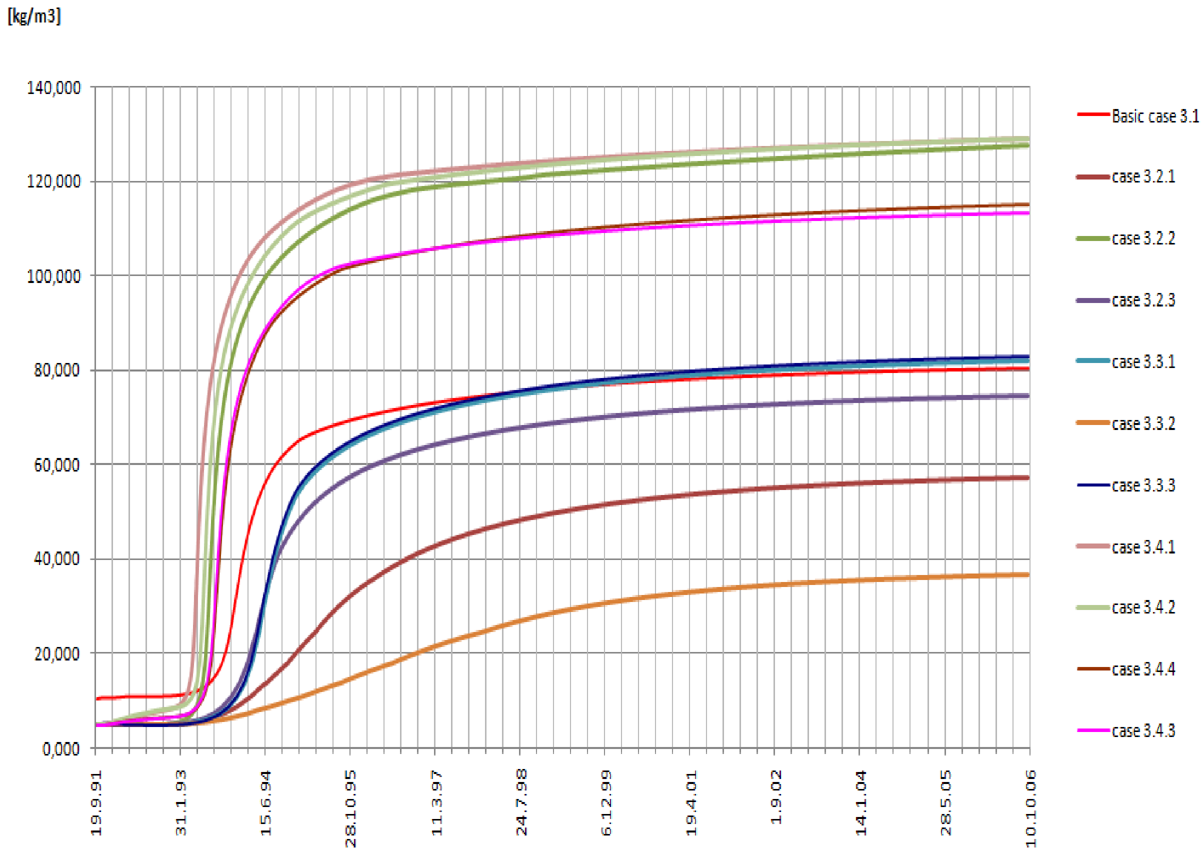

Chart 3.6.1 water content in point 24

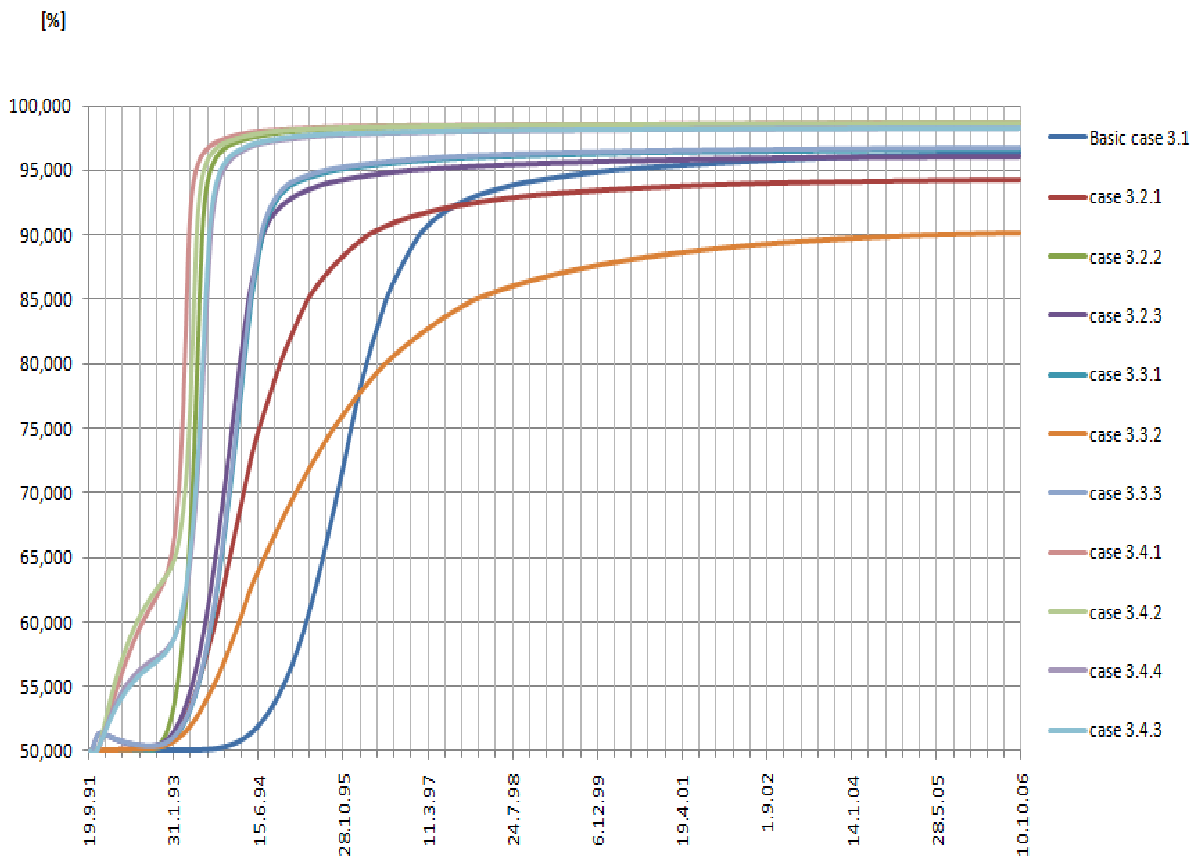

Chart 3.6.2 relative humidity in point 24

As can be seen in the chart 3.6 water content in the middle of the structure (point 24) is a little bit bigger than on the surface (point 23). But we can observe a big difference of relative humidity between the points.

In table 3.2 have done comparison between water content and the relative humidity in the whole structure by height level. Relative humidity is expressed in "%" in the below shown table, but this "%" doesn't mean RH by itself, this "%" expresses only the height level of relative humidity. The height level of moisture ranged 97-100% was taken equal to 100"%". The real level of water is a very important value, if we think about application of rehabilitation methods and it is efficiency.

Table 3.2 Comparison WC and RH in the whole structure

Designation of case	Water Content, [m]		Relative Humidity, [%]	
	Level	Difference	Level	Difference
3.1 Basic case	1,72	0	100	0
3.2.1	1,42	-0,30	87	-13
3.2.2	2,74	+1,02	152	+52
3.2.3	1,70	-0,02	100	0
3.3.1	1,62	-0,10	93	-7
3.3.2	1,32	-0,40	85	-15
3.3.3	1,55	-0,16	91	-9
3.4.1	3,00	+1,28	167	+67
3.4.2	3,00	+1,28	169	+69
3.4.3	2,46	+0,74	132	+32
3.4.4	2,51	+0,79	133	+33

From the above shown table can be seen that water level in the basic case reaches 1,72 m over floor level, after application of rehabilitation technology 3.3.2 water level was reduced to 0,4m and level of relative humidity also was reduced to 15%.

4. INJECTION METHODS

Injection techniques (chemical methods) have become established across the market over the last few decades. For many years, the main reason was seen to be that injection systems provide a price advantage, when considering the economical means to carry out a rehabilitation measure with alternative methods. Meanwhile, the injection systems have taken on a leading role since many fundamental investigations have been undertaken and limitations, thus, been defined. Professional and qualified application can lead to similarly good results with these methods as with physical methods. Injections are, therefore, the most commonly used method for, or rather, against rising damp. They currently take up a market share of about 70 %, with a tendency to increase. (Frossel, 2006)

In contrast to physical methods, injections have the advantages that they can be carried out from outside or from inside, from outside and inside, as well as at different heights of a masonry. Injections around the foundation are possible, as well as around the base or below the basement ceiling. If they are carried out from one side, they possess the advantage that only one face of the masonry is optically impaired, assuming, of course, that the injection material does not emerge on the other side. For injection methods, an injection material is introduced in a drilled-hole with or without pressure. Even, if the distribution of the injection material around the drilling entrance can sometimes still be optically controlled, the distribution and effect within the building material cannot be controlled anymore. Nonetheless, most planners and many users don't know the reaction mechanisms and modes of action of injection materials. It is, however, exactly these two aspects that affect whether an injection is suited or whether the effectiveness of the substance can develop in the masonry. If the mechanisms of action cannot function because, for example, the reaction and object conditions are not given, water-repellent impregnation is prohibited. Reaction conditions and mechanisms of action have to be known for this. Some injection materials do not react, for example, if an elevated degree of dampness or capillary saturation is present in the masonry. Others, in turn, specifically require water for the chemical reaction.

Injection methods are differentiated in: pressure injection, unpressurised injection and impulse injection. Before presenting the different technologies, injection methods shall be defined in general: injection methods or chemical injections signify the introduction of an injection fluid in a masonry wall, whereas the injection maybe carried out with or without pressure. The technology needs to ensure that the injection material is spread over the whole masonry cross-section and that an effective continuous barrier layer is formed. For this purpose, holes with a diameter of 16 to 25 mm are drilled in the masonry at 100 to 150 mm spacing, in one, two or three rows. The hole is drilled at an angle of 10 to 45°. The depth of the hole is equal to the wall depth minus 50 to 100 mm, under consideration of the drill angle.

4.1 Unpressurised injection

With unpressurised injection, the injection material is filled into the hole without pressure, so that the penetration or distribution of the material was achieved through gravity. For the injection material to spread in such a manner, it needs to possess good plastic and penetration properties. Therefore, water soluble, low-viscosity injection materials are most suited, such as siliconates, silanes, silicone micro emulsions or sufficiently heated paraffins.

Since the distribution of the injection material exclusively follows the law of capillarity, only masonry with a degree of dampness of max 60% can be injected. The maximum spacing between the holes needs to be selected based on the absorbing capacity of the material and the penetration properties of the injection material; it should be, however, no less than 100 mm or more than 150 mm. The diameter of the hole depends on the method employed and should in average be around 20 mm. (Frossel, 2006)

The injection materials are exclusively filled into the holes with a watering can (see in the figure 4.1). The user, however, has no control of the amount of injection material necessitated for each hole or whether the injection material was actually running into cavities and the like. A development of injections is to use transparent funnels to fill the holes. This means that the amount of injection material used for every hole can be better observed. Today, unpressurised methods are nearly exclusively performed by means of reservoir bottle injections (see in the figure 4.2). This has the advantage that the injection material can permanently spread in the hole. It helps to ensure that the water-repellent effect of the injection material does not already set off during injection.

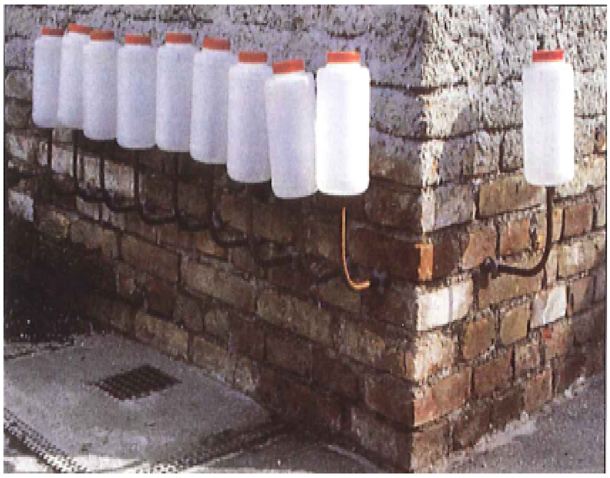

Figure 4.1, 4.2 Unpressurised injection (Frossel, 2006, p.108)

With unpressurised methods used nowadays, bottles are placed in prepared holes at a slight angle, so that the injection material can penetrate via the walls of the holes. In contrast to unpressurised methods, where holes are filled manually with a watering can, reservoir bottle injection enables observation and sometimes documentation of hole-specific injection material consumption. The disadvantage of reservoir bottle injections is, for one part, the manual, and thus, time consuming filling of holes and, for another part, the exclusively unpressurised distribution of the injection material. Reservoir bottle injections, as well as other unpressurised injection systems have the disadvantage that the distribution of the injection material in masonry is not or barely achievable in very damp walls. (Frossel, 2006)

Preparation of the masonry helps preventing uncontrolled flow of injection materials. It should, hence, be in the best interest of all those affected to not only improve the distribution of the injection material in the masonry but also to reduce the injection material consumption, and thus, the costs. Since, with the reservoir bottle injection, injection materials can be injected via reservoirs, the original inclination of the hole of about 45° has been reduced to an angle of 10 to 30°. This enables homogeneous and regular distribution. (Frossel, 2006)

4.2 Pressure injection

Pressure injections are particularly useful for very damp or capillary saturated masonry because even pore spaces that are not accessible through capillarity are filled with injection material. For this purpose, holes are drilled at 100 to 300 mm spacing and with a diameter of 15 to 25 mm. The hole is drilled horizontally or with a downward angle of up to 20°. If the joints are stable enough, it is common to drill the holes horizontally. Because of the pressurised injection and the expected better radial distribution of the injection material around the hole, pressure injections can be made in one row only. Deviations from these specifications are possibly method-related and/or object-independent. The masonry cross-section has to be made up, so that the injection material cannot run off uncontrolled. In some cases, the masonry has to be injected beforehand with a special suspension. (Frossel, 2006)

The hole has to be set in a way that at least one, better two horizontal joints are intersected or, if drilled horizontally, they should be in the horizontal joint. The depth or length of the hole is equal to the wall thickness minus 50 mm, under consideration of the angle of the hole. Pressure injections are differentiated into low and high pressure injections. Low pressure injections are performed with at least 2 to 3 and maximum 10 bar. High pressure injections start at 10 bar and are not limited upwards. Especially with high pressures, it is always important to remind people that this is associated with dangers for the user and damages of the building substance cannot be excluded. Inhomogeneous and weak masonry sets other requirements than a compact concrete component. When filling cracks in the context of concrete restoration, pressures of up to 100 and more bar are usual. To analogically transfer this to injections against rising damp is unreasonable and unnecessary. Principle of pressure injection shown in the figure 4.3, 4.4, 4.5

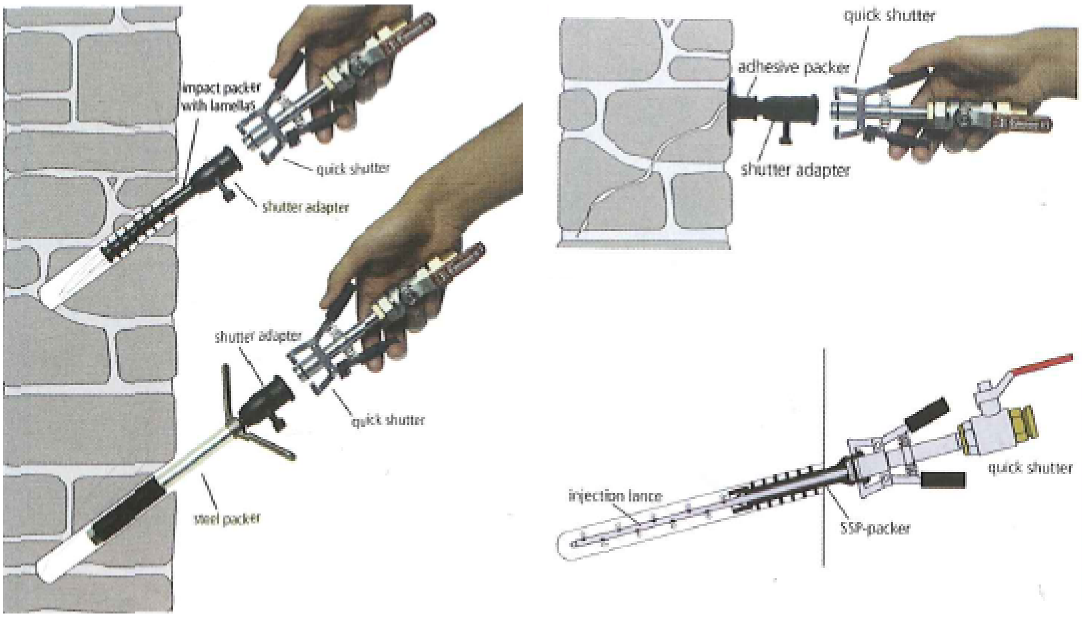

Figure 4.3, 4.4, 4.5 Principle of pressure injection (Frossel, 2006, p.111)

Investigations have shown that already continuous low pressures (< 10 bar) can sufficiently distribute the injection material. If the pressure build-up is not sufficient, it needs to be checked how much of the injection material can run off uncontrolled through cavities or in jointed and/or cavity constructions. Additionally, no or insufficient pressure is built up if cracks and/or open joints let the injection material run out. Increasing the pressure, in this case, does not do much. Special preparation and pre-treatment of the masonry is necessary. In practice, cavities and cracks in the masonry cross-section are sealed with a preliminary injection or the joints of the masonry are grouted. Alternatively and if present, the old plaster is simply left on the wall until after the injection. This helps preventing the injection material from running out. It is important that the pressure actually builds up in the masonry and does not drop within a period of max. 10 minutes. (Frossel, 2006)

To be able to fill the injection material into the masonry under pressure, special devices need to be organized around the hole. The pressure-resistant devices or connections are referred to as injection packers or anchors. Injection packers can be made from plastic or metal and are differentiated into drill-, impact- or screw-packers. From time to time, they are referred to as adhesive-packers or injection tubes, whereas this system is known from crack filling, hence, the firm sealing of concrete members through injection. Packers can be seen in the figure 4.6, 4.7, 4.8, 4.9.

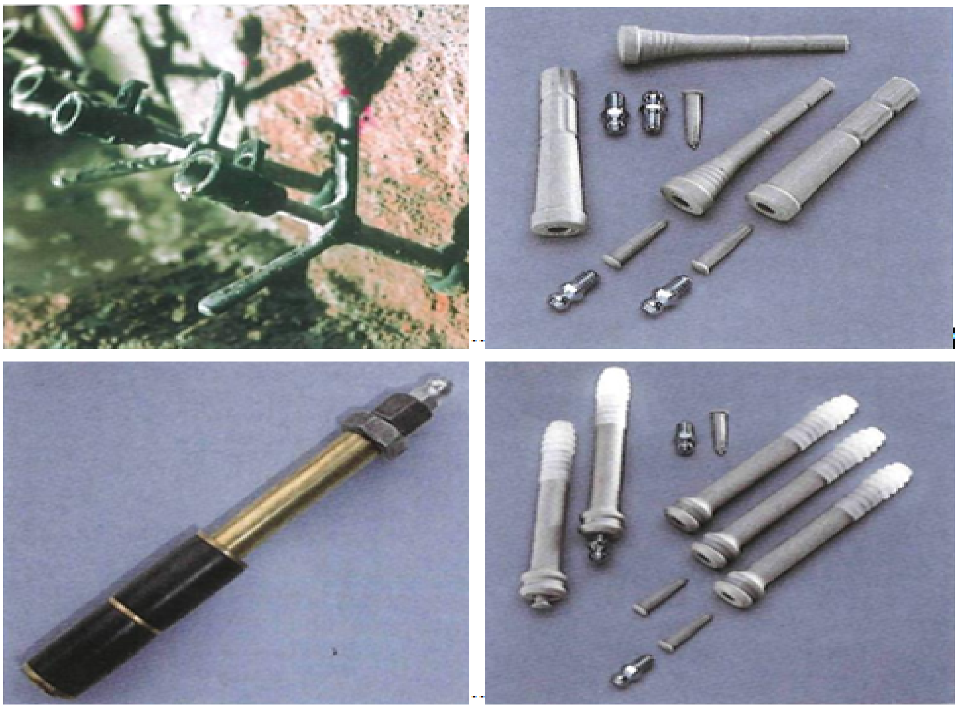

Figure 4.6, 4.7, 4.8, 4.9 Different packers for injection (Frossel, 2006, p.112)

Drill- and screw-packers are usually made from metal and are screwed or locked into a specially synchronized hole with the same diameter. A deformable rubber collar within the thread guarantees the seal between the hole and the injection-packer. It has to be ensured that the masonry is pressure resistant enough, so that the injection packer sits firmly. The connection to the injection machine is formed via a, so-called, injection nipple. A non-return valve in this one ensures that, for one, the injection material does not run out and the pressure can build up within the hole. (Frossel, 2006)

Impact-packers are made from hard plastic and are driven into the hole. The seal in the hole is achieved through lamellas that tilt while being driven in, hence, hook in. Like the previously mentioned packers, the impact packer also possesses a non-return valve, preventing running out or return flow of the injection material. The advantage of these injection packers is that smaller holes can be drilled. A further advantage is fast installation and often the unit price. Nevertheless, packers have the disadvantage that they cannot be post-tightened during injection. For this reason, they have to sit firmly once driven in to ensure the contact point is tightly sealed. For injection methods with a higher pressure, these packers should only be employed if the material quality is good.

When injecting injection materials, so-called, injection pumps or instruments are used, which are differentiated based on how they operated. Membrane or airless instruments, piston jack pumps, screw presses or toggle joint presses are used. Apart from vacuum pumps, special injection pumps are used, where different injection instruments can be combined. Injection pump can be seen in the figure 4.10

Figure 4.10 Injection pump (Frossel, 2006, p.113)

Differentiation is made based on the composition of the injection material. Single- or multi-compound injection pumps are on offer. With the first-mentioned, the injection materials are mixed or diluted and placed in the reservoir of the injection pump. Alternatively, single-compound injection materials are directly processed from the mix. It has to be taken into account that the processing has to be completed within the, so-called, liquid pot life, so that the reaction does not negatively affect the penetration behaviour of the injection material. The disadvantage is that only so much material can be mixed or diluted, as can be injected during a specified time span. After every interruption, the injection pump has to be cleaned thoroughly. With injection pumps that are set out for multi-compound injection materials, the compounds are handled separately and only mixed immediately before injection. This has the advantage of the injection pump not requiring cleaning in between, even in case of interruption. (Frossel, 2006)

Injection pumps have to be cleaned thoroughly and conscientiously, so that contaminants and impurities cannot impair the injection process. Furthermore, it should be ensured that all cleaning water is completely removed from the pump and no condensate is formed, when injection materials are used that can react with water. The injection pump should, in principle, be in keeping with the regulations set by the professional or trade association and fulfill the requirements in relation to masonry injections. (Frossel, 2006)

Pressure injections are good to use with high degrees of dampness, with a capillary saturated or capillary inaccessible pore structure and geometry in a material. Additionally, pressure injection ensures quick distribution of the injection material within the capillary system and reduces the residual risk of injections. Moreover, the competency of a specialist increases if the injection is not performed uncontrolled manually or using reservoir bottles. (Frossel, 2006)

4.3 Impulse injection method

The impulse injection method has established itself as the third group of injection systems, over the last few years. This is a modern injection technology, eliminating the application limitations of traditional reservoir bottle injections and bringing good system dependability. The method is patented and has been employed in Central Europe for about 15 years. Impulse injection method can be seen in the figure 4.11, 4.12

Figure 4.11, 4.12 Impulse injection method (Frossel, 2006)

An impulse instrument injects an injection fluid into the masonry at intervals. An electronic control on the impulse instrument regulates the supply of the injection material, depending on the base- and/or object-specific conditions. Impulse times, injection times, as well as the length of the breaks between injections vary. The injection fluid coming from the impulse instrument is fed into perforated infusion tubes via a feeding system. These infusion tubes ensure that the injection fluid is distributed across the whole masonry cross-section. Preparation of the masonry, such as the filling of cavities, etc. is not necessary because of the perforated infusion tubes. Because the impulse system is exclusively offered with silicone micro emulsions, very damp masonry can be injected as well. (Frossel, 2006)

Injection times can be set individually from 0.5 to 2.5 sec and the breaks in-between from 1 to 10 minutes. At the beginning of an injection, injection times are long and breaks short because the building material can still take up relatively large quantities of injection material. With increasing injection times, the impulses become shorter and the break times longer, so that the hole is only fed as much injection material as it can adsorb. A second important characteristic of the method consists in the distribution of the injection material via perforated infusion tubes (figure 4.13). These infusion tubes, also referred to as injection- or spray-lances, have a perforation that is offset at 60 to 80 mm spacing with a diameter of < 1 mm. The injection material exits these openings at each impulse and wets the interior walls of the holes.

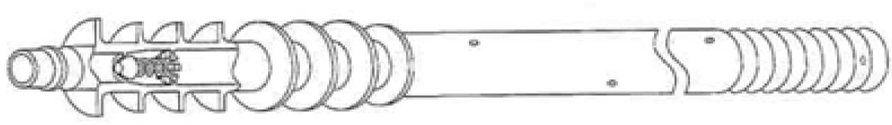

Figure 4.13 Perforated injection tube for impulse method (Frossel, 2006)

With this lance technique, hollow, jointy or multiple-leaf masonry can be injected, without requiring previous filling with a slurry or suspension. Moreover, the whole masonry cross-section is injected because the injection material is distributed via the whole length of the infusion tubes. The penetration and distribution of the injection material is, thus, much higher than with conventional methods. (Frossel, 2006)

Rising damp can appear within materials and not in cavities. To ensure that the injection material is not exclusively sprayed into the cavities, the injection time and pressure are adjusted to the masonry and set accordingly. Because the external diameter of the infusion tubes is 16 mm and the internal diameter of the hole is 18 to 20 mm, the infusion tubes are in contact with the masonry. The impulse causes the injection material to immediately penetrate the material. Before the counterpressure builds up, the impulse is already over and the break time set. For material loss to stay relatively low and the building material to be able to adsorb the injection material, the impulse time, the break time and the injection/spray pressure have to be adjusted for every masonry wall.

The advantage of impulse systems is, without a doubt, that the injection process is controlled electronically and the method, hence, runs autonomously. Other work can then be carried out at the same time. The distribution of the injection material across the whole masonry cross-section without previous filling of the cavities benefits the cost optimisation, without reducing the quality and method security. It is exactly these advantages that bring a significant disadvantage. If the degree of dampness and the material porosity vary within a masonry wall, alternative systems are more advantageous, where every hole is individually injected. This helps to ensure that these varying masonry parameters are taken into account. Via the feeding system, the impulse system can fill 8 m running (or 64 holes) at the same time. This means that every hole receives the same amount of injection material, independent of the individual degree of dampness. For this reason, it is impossible to make specifications for the injection material consumption of every hole; it can only be made for 8 m running. (Frossel, 2006)

4.4 Materials which have used for injection

Before describing the individual injection materials, the requirements set for all injection materials have to be defined. These requirements have to exceed the originally mentioned smallest common denominator and form qualitative criteria for the selection of injection materials. To ensure the effectiveness and continuity of a retrofitted horizontal damp proof course, the injection material should: be easily distributed in moist (until saturated) and salt-laden masonry, possess a good penetration depth, not form any salts or other structure damaging by-products, have a sufficiently long reaction time to achieve optimal penetration depth, be useable with every building material. This would mean that injection materials should have a low molecular weight and should be formulated to be salt-free and water-compatible. Classical emulsions and suspensions, as well as highly polymeric matters are less well suited because of their small penetration depth.

4.4.1 Cement suspensions

Cement suspensions have already been considered to be unsuited or only conditionally effective as injection material against rising damp, for a long time. Particle size and viscosity prevent sufficient distribution within the pore structure of commonly used materials, such as bricks, natural stone or joint mortar. A kind of water-repellent clot is merely formed in the drilled holes. Cement suspensions should, therefore, not be offered as actual injection material, but for pre-injections in hollow, jointy or multiple-leaf masonry. The use of HS-cements provides good resistance against sulphate-laden bases or masonry cross-sections. Much has been done in this respect, over the last few years, to reduce the shrinkage behavior. (Frossel, 2006)

4.4.2 Alkali silicates

Alkali silicates, sodium- and potassium silicates, colloquially also referred to as water glasses, have already been used for decades to damp proof masonry walls. Silicates are the salts of the silicic acid that are, for example, formed during the reaction of quartz with caustic soda or potassium hydroxide solution at high temperatures. (Frossel, 2006)

While sodium compounds were mainly used previously, today, potassium silicates or potassium water glasses are used, even if only from time to time. The products are made from strongly alkaline, watery solution. Often, a stabilizer and other auxiliary agents are added to the injection material. Once introduced into the pore system, the alkali silicates slowly release a silica gel, thus, narrowing the capillaries of the material (capillary radius > 0). This could, in theory, bring a reduction in capillary absorbing capacity. Because of the evaporation of the water, however, the silica gel shrinks, and hence, causes the formation of the so-called secondary capillaries. These could again bring an increase in capillary activity once the silica gel in the pores has completely dried out. This, in consequence, leads again to capillary conductivity, and thus, renewed moisture penetration in the building material. (Frossel, 2006)

Moreover, potassium- and sodium-silicates introduce an elevated alkali-content, which converts with the carbonic acid in the air to large amounts of potassium carbonate or soda. These soluble and structure damaging salts burden the masonry additionally. Low-alkali silicate compounds are, therefore, preferably employed to keep the salt formation to a minimum. This appears as widespread efflorescences on the masonry. It can also occur within the masonry due to crystallization, with the consequence that hygroscopic moisture can emerge again. The use of pure water glass solutions as injection material is, for this reason, very alarming. (Frossel, 2006)

4.4.3 Epoxy resins

Epoxy resins are the most relevant liquid plastics on the injection market. This is not least due to the very good chemical and physical properties. Alkali resistance and affinity to mineral bases are certainly the two most important properties. The use of epoxy resins for injections against rising damp has, however, the disadvantage that the rigidly dry product becomes too solid. Moreover, the water vapor diffusion behavior is worse. (Frossel, 2006)

Liquid epoxy resins require reaction partners to react and harden; these are present as liquid amines and react with the epoxy groups to macro molecules. Apart from this kind of epoxy resins, the so-called hardener influences the course of the chemical reaction, hence, the properties of the injection materials. Epoxy resins can lead to strong contamination on exposed masonry, which are irreversible, and thus, can only be removed with much effort. (Frossel, 2006)

4.4.4 Polyurethanes

A further group of organic resins are the polyurethanes, Here, polyols and isocyanates are employed as most common reaction partner. Water from the ground (material capillaries, water-conducting cracks, etc.) is also used as reaction partner for this reaction. With the hardener component, polyether is formed in a chemical reaction, while carbon dioxide is split off simultaneously. This expansive reaction additionally brings a sealing effect, resulting from blister formation within the structure. (Frossel, 2006)

With the selection and coordination of product components and reaction partners, different properties can be created. Polyethers show noticeably better durability than polyesters. An essential property of all polyurethane resins is the particularly high elasticity, which is not even affected to a great extent below the freezing point. (Frossel, 2006)

4.4.5 Silicone micro emulsion concentrates

Silicone micro emulsion concentrates represent a novelty compared to other injection materials. These injection materials have been used since the beginning of the 1990s; the breakthrough was only achieved in the late 1990s. Because of their application flexibility, as well as their important product advantages compared to classic injection materials, the term silicone micro emulsion concentrate-technology is already often employed nowadays to describe water- and solvent-free silicone micro emulsion concentrates. (Frossel, 2006)

Silicone micro emulsion concentrates are low-viscosity, clear, water- and solvent-free liquids that spontaneously form extremely fine and stable silicone micro emulsions when poured into water. The particle size of these watery silicone products ranges from about 10^{-9} to 10^{-10} m, referring to the radius. They are, hence, a few decadic quotients smaller than the particles in common emulsions. The thus formed emulsion is then particularly fine and, therefore, well suited as injection material. (Frossel, 2006)

Silicone micro emulsion concentrates are at least 12 months storage stable and effective, if in the form of a sealed pack. Because the ingredients are reactive, condensation-curing components, silicone micro emulsion concentrates keep these properties only in their water-free form, hence, as concentrate. Silicone micro emulsions, with only temporarily effective silicone tensides, are modifiable, solvent-free silan/siloxane mixes. They can be spontaneously diluted in water and then form a fine micro emulsion. Physical drying leads to condensation of these (while splitting off alcohol) to a non re-emulsifiable poly siloxane. Their chemical structure enables them, on one side, to bond with the base and, on the other side, to produce a water-repellent effect, without, however, impairing the diffusion capacity of the material. Alkalinity accelerates the curing reaction. (Frossel, 2006)

It is certainly generally known that the particle size is also stable or preserved if the silicone micro emulsion concentrate is diluted in water. This means that the particles, with a size of approximately 10^{-9} to 10^{-10} m, referring to the radius, are still present after a few years. The reactive ingredients, however, already start to react within the droplets as soon as they come into contact with water (droplet condensation). The silicone micro emulsion slowly loses its effectiveness, as a result. The loss in effectiveness from the point of dilution lies around one week. Because the silicone micro emulsion starts to flocculate after about 24 hours, it has been suggested to apply the prepared injection material within one working day. The time-delayed effect of silicone micro emulsions is an ideal precondition for the penetration of the injection material because it can penetrate the capillaries in watery dilution, without reacting directly and can develop the initial hydrophobicity within one week. It should, therefore, always be ensured that the physical drying of the silicone micro emulsion takes place in the week after injection. (Frossel, 2006)

Silicone micro emulsions, in the form of watery injection material, are capable of mixing with the pore water of the material, so that even with high degrees of dampness, a good penetration depth and distribution is achieved. (Frossel, 2006)

5. CONCLUSIONS

The most important result is that we have the possibility to compare different rehabilitation methods by calculations and choose the best. It is very useful when structure can be analyzed during some period of time. Via the WUFI 2D can be done prediction about moisture behavior; which helps avoid problems that can occur in the structure after some period of time.

One of the most important achievements was the creation of climate file in the WUFI 2D, which corresponds to water level condition and makes possible to the structure to absorb as much water as it can.

During the investigation was considered a standard structure, with study its possibility to absorb water, and were considered ten rehabilitation methods with identical and different ambient conditions. Received results have shown that the same effective rehabilitation method is the application of high porosity plasters with horizontal injection. The application of vapor proofing barriers, for instance metal foils, leads only to increasing amount of water within the structure. All results have been considered in chapter 3.5. more detailed.

Injection technologies were observed and submitted, because they are the most commonly used methods against rising damp and they currently take up a market share of about 70 %, with a tendency to increase. All considered technologies have got limits of applicability and their own advantages and disadvantages. Everything depends from specific structure conditions, such as: water content, amount of salts, types of salts and their distribution in the structure. That is why it is difficult to choose absolutely the best injection technology. But impulse injection technology, which has got a lot of advantages can be distinguished, for instance: injection fluid is distributed across the whole masonry cross-section; preparation of the masonry, such as the filling of cavities, is not necessary; the injection process is controlled electronically and the method runs autonomously.

Also need to say, about modeling injections in thesis. In real life when we use injection, structure has already been in saturated conditions and injection prevents the coming of new moisture. But in my investigations injection was embedded in totally dry model of structure. It was done for unification all cases, but it can give inaccuracy, if we think about real injections technologies.

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4. WUFI 2D

Table 1: The μ-factor for some materials.(Hagentoft, 2001, p.97)

Material	μ -factor (-)
Mineral wool, lightweight concrete, brick, lime mortar Concrete, wood, lime cement mortar Linoleum, PVC-foil, polyethylene foil, glass	1-10 15-100 10^3 - 10^6

Table 2: A-value for some materials (Hagentoft, 2001, p.102)

Material	A (kg/m^2√s)
Brick (p = 1700	0.4
Brick (p = 1900 kg/m^3)	0.1
Lightweight concrete	0.1
Concrete W_o/C=0.3	0.01
Concrete W_o/C=0.5	0.02
Concrete $W_0/C=0.7$	0.03
Cement mortar	0.03
Lime mortar	0.3
Wood ‖ to fiber	0.02
Wood ⊥ to fiber	0.004

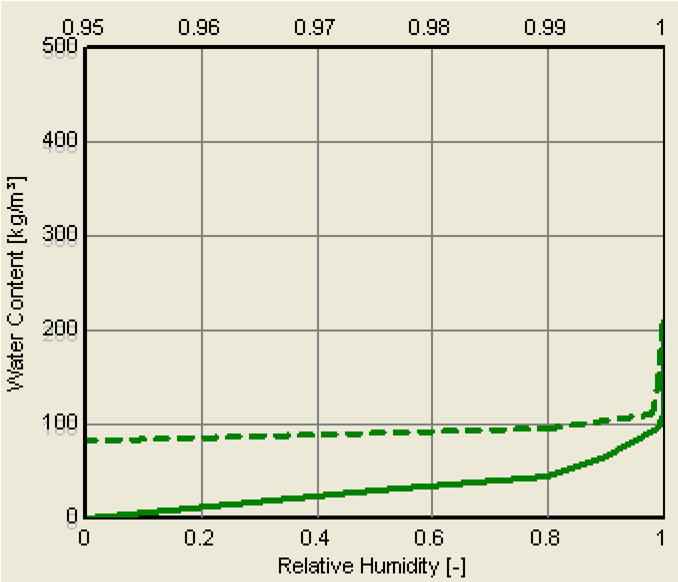

Figure 1.1: Moisture storage function for lime cement plaster

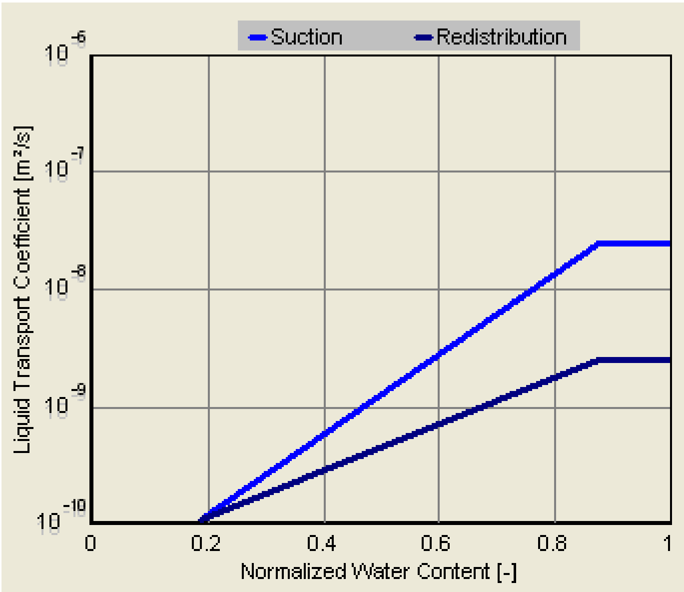

Figure 1.2:Liquid transport coefficient for lime cement plaster

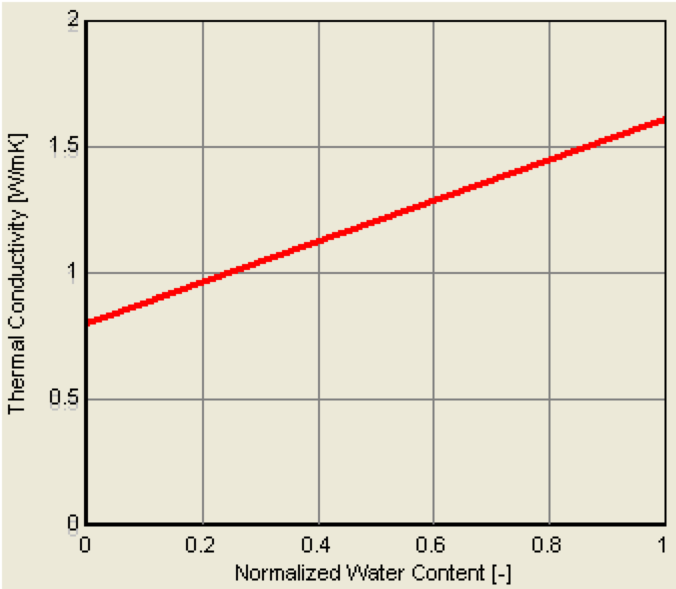

Figure 1.3: Thermal conductivity for lime cement plaster

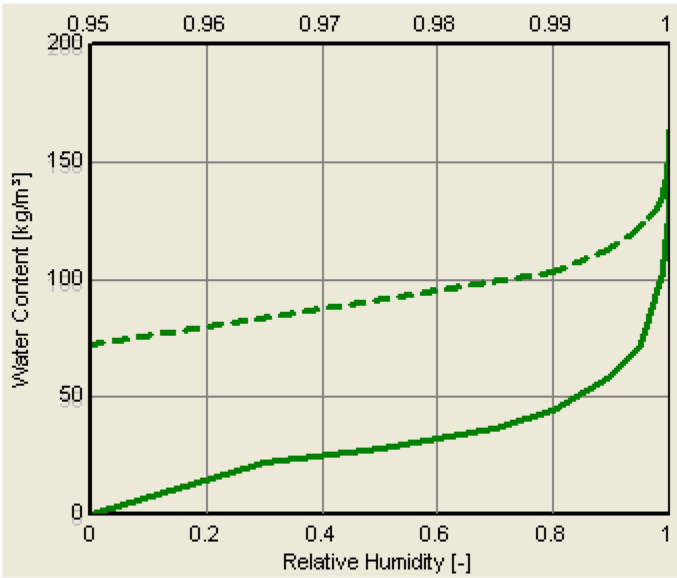

Figure 2.1: Moisture storage function for rehabilitating plaster (high porosity)

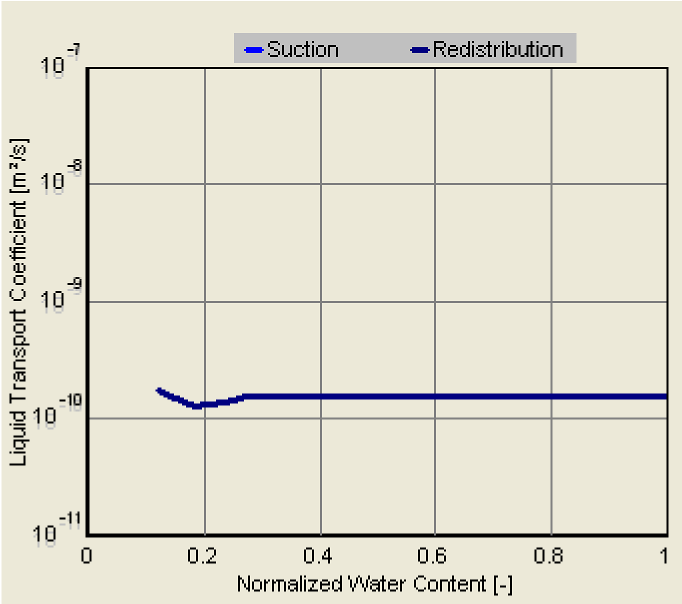

Figure 2.2: Liquid transport coefficient for rehabilitating plaster (high porosity)

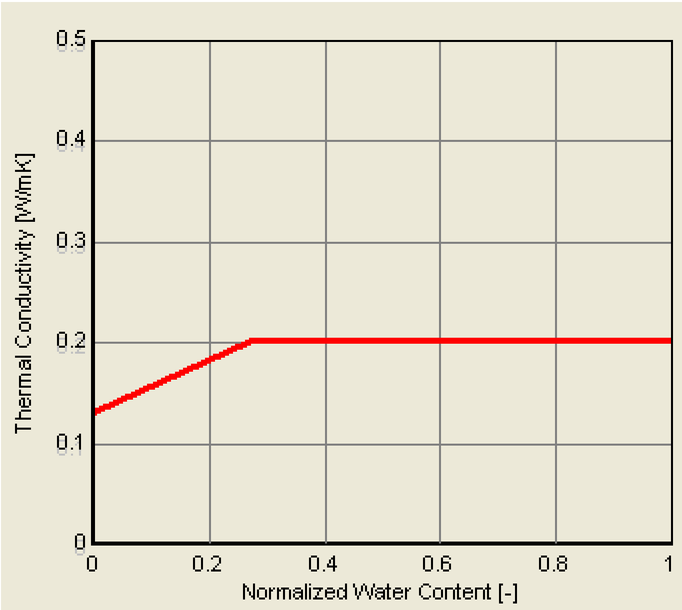

Figure 2.3: Thermal conductivity for rehabilitating plaster (high porosity)

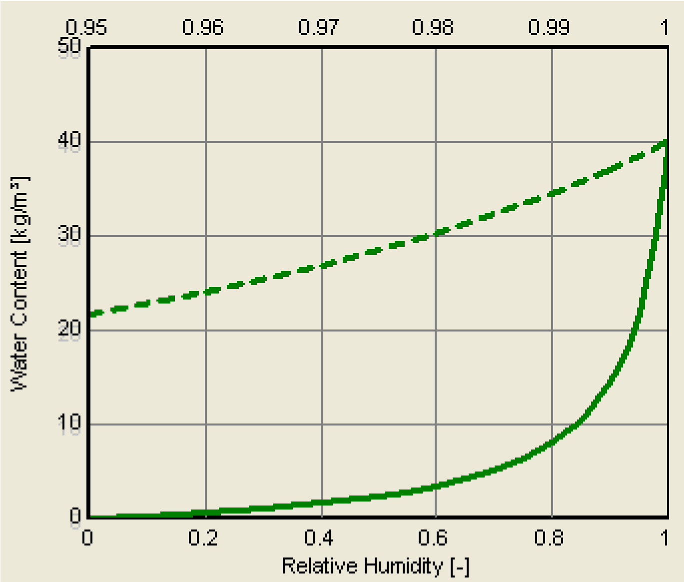

Figure 3.1: Moisture storage function for injection

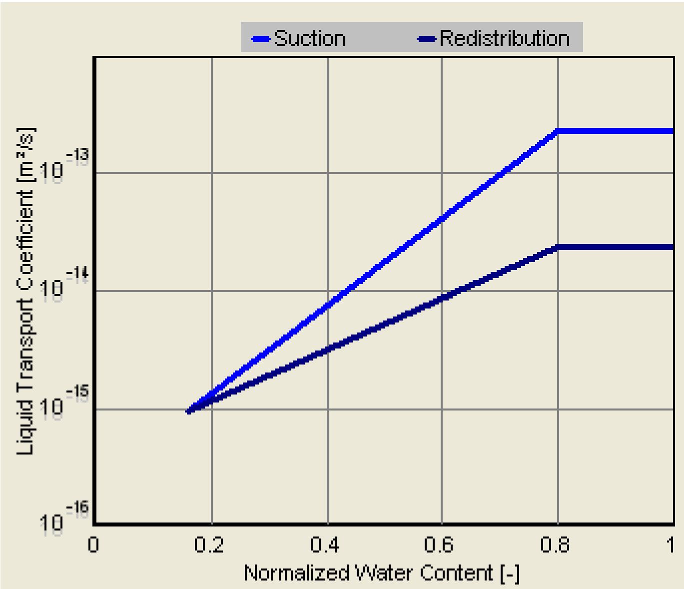

Figure 3.2: Liquid transport coefficient for injection

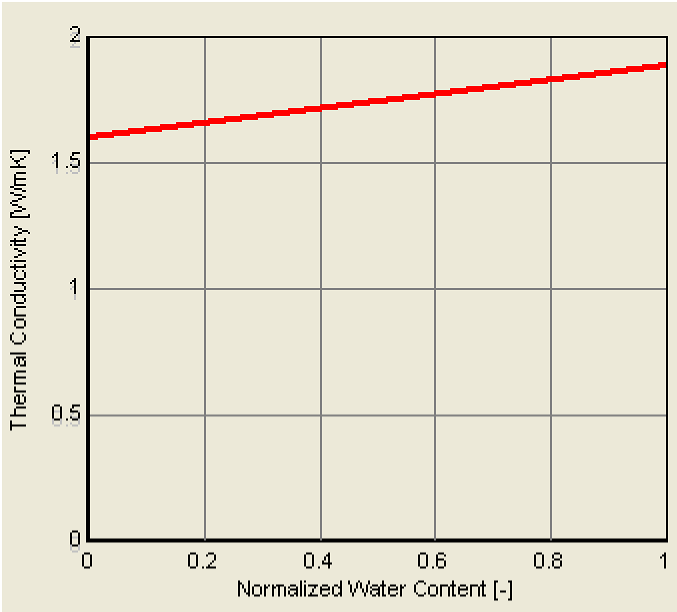

Figure 3.3: Thermal conductivity for injection

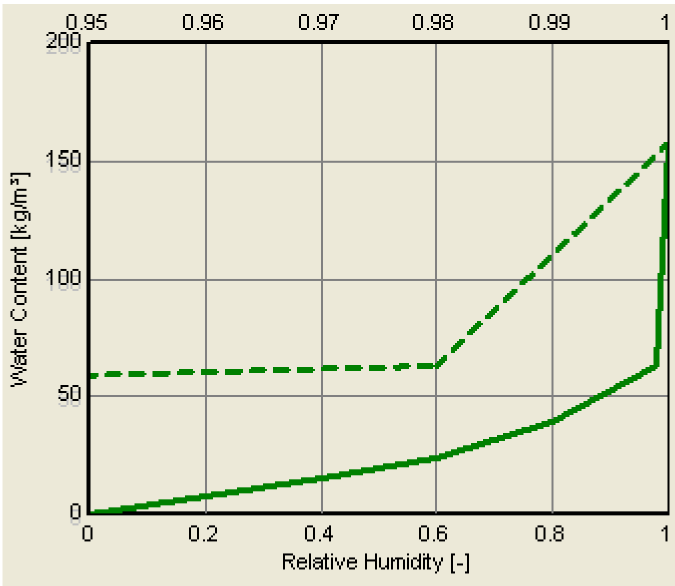

Figure 4.1: Moisture storage function for sand

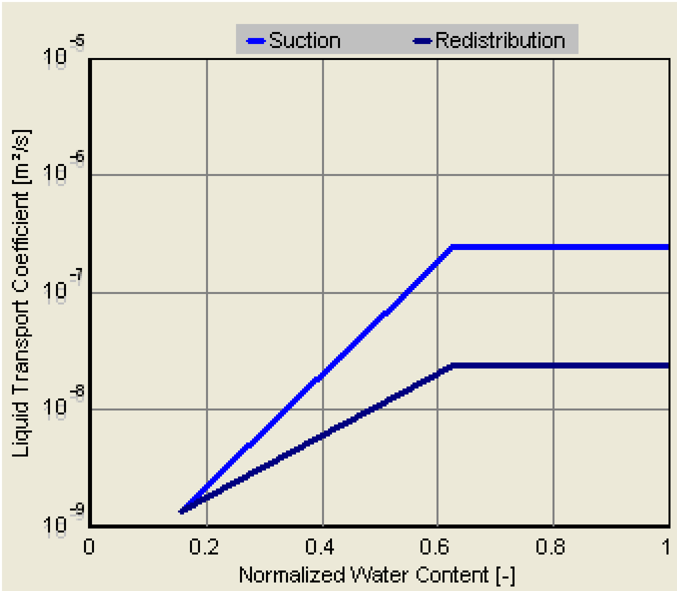

Figure 4.2: Liquid transport coefficient for sand

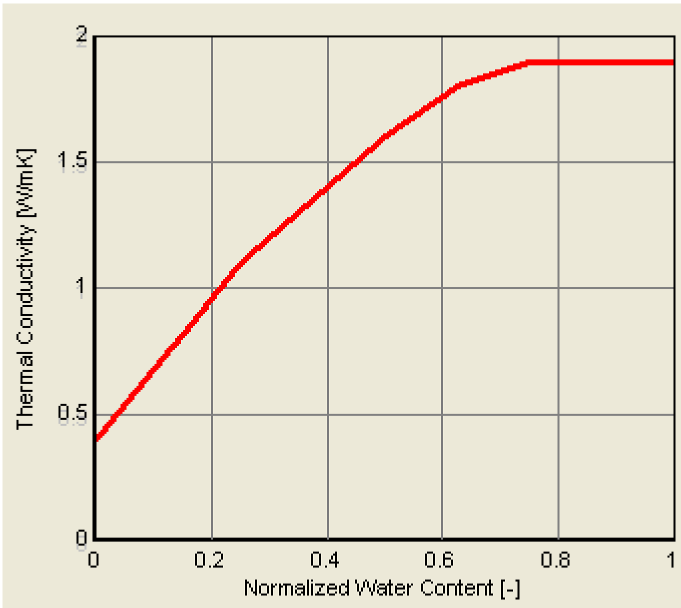

Figure 4.3: Thermal conductivity for sand